Computer Networks

Chapter 2
Application Layer

Adapted from Book Slides: “Computer Networking: A Top-Down Approach”

Chapter 2: outline

- Principles of network applications
- Web and HTTP
- Electronic mail (E-mail)
  - SMTP, POP3, IMAP
- The Domain Name System (DNS)
- P2P applications
- video streaming and content distribution networks

Application layer: overview

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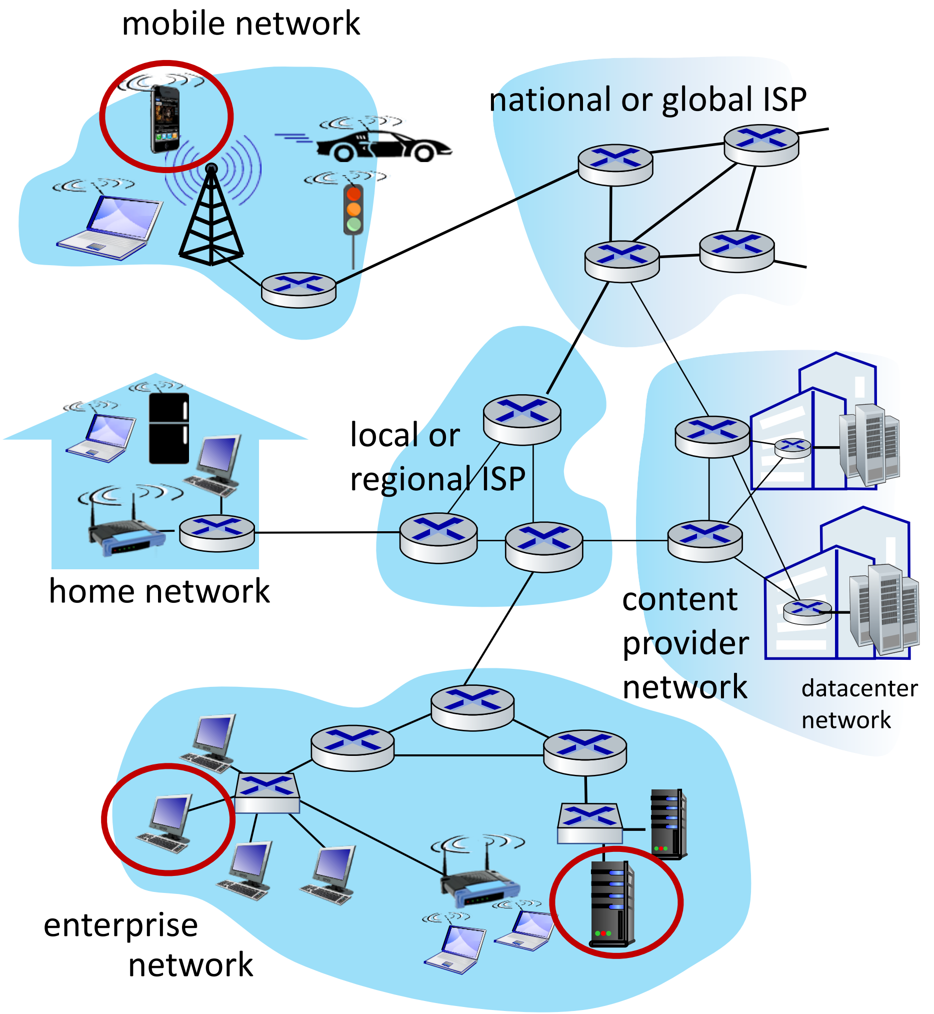
write programs that:

- run on (different) end systems
- communicate over network
- e.g., web server software communicates with browser software



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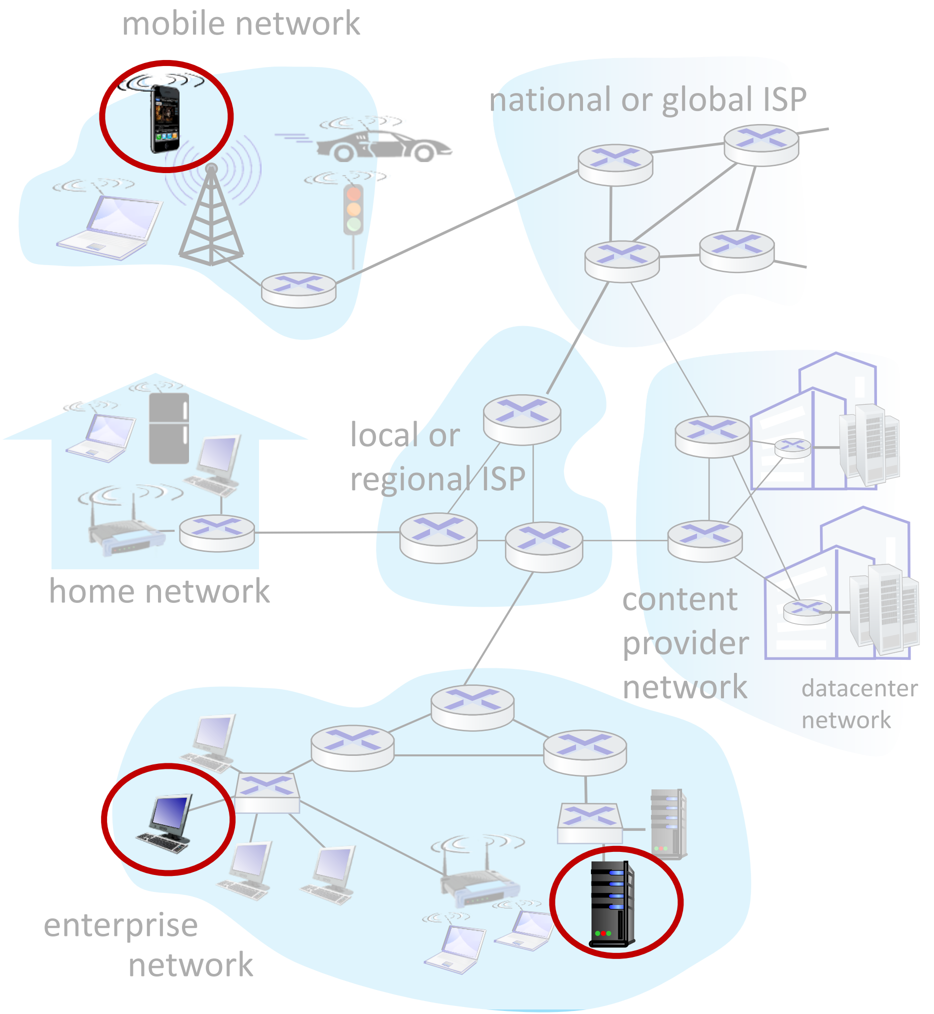

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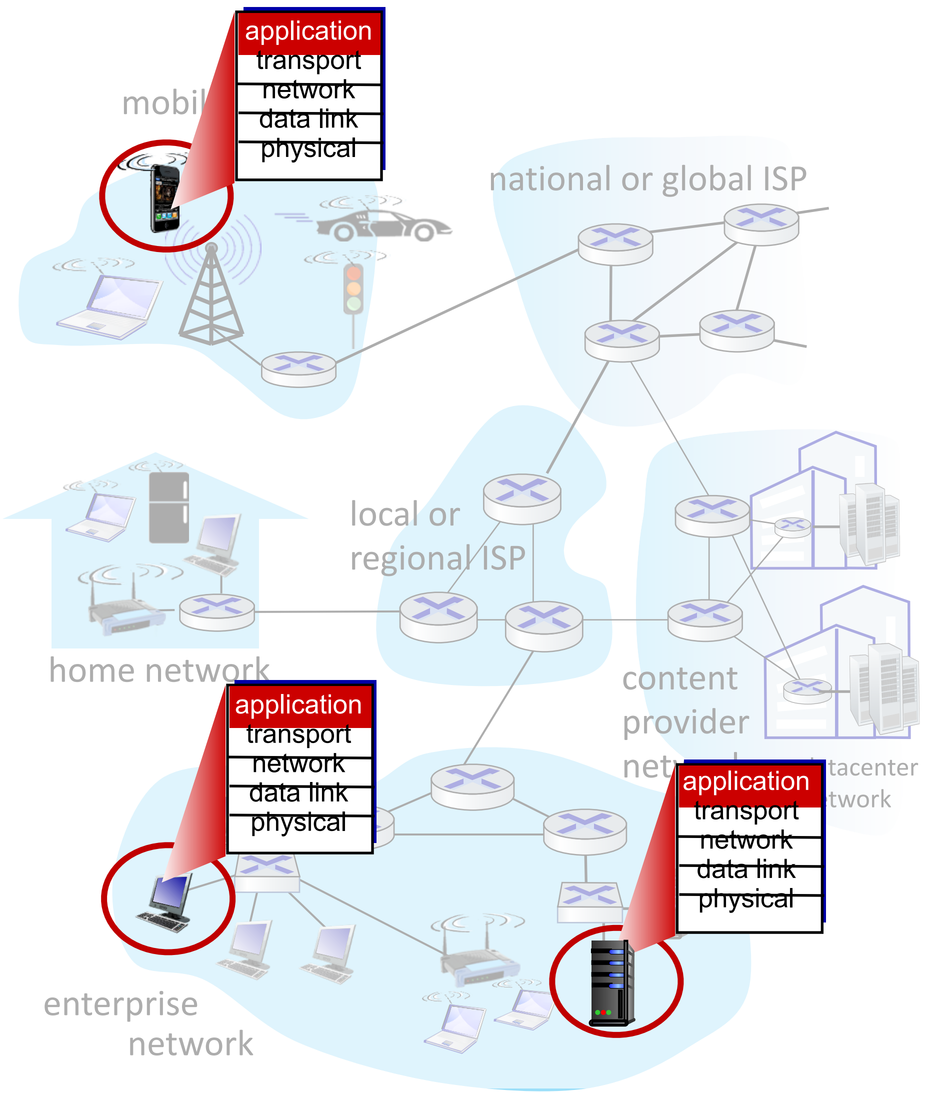

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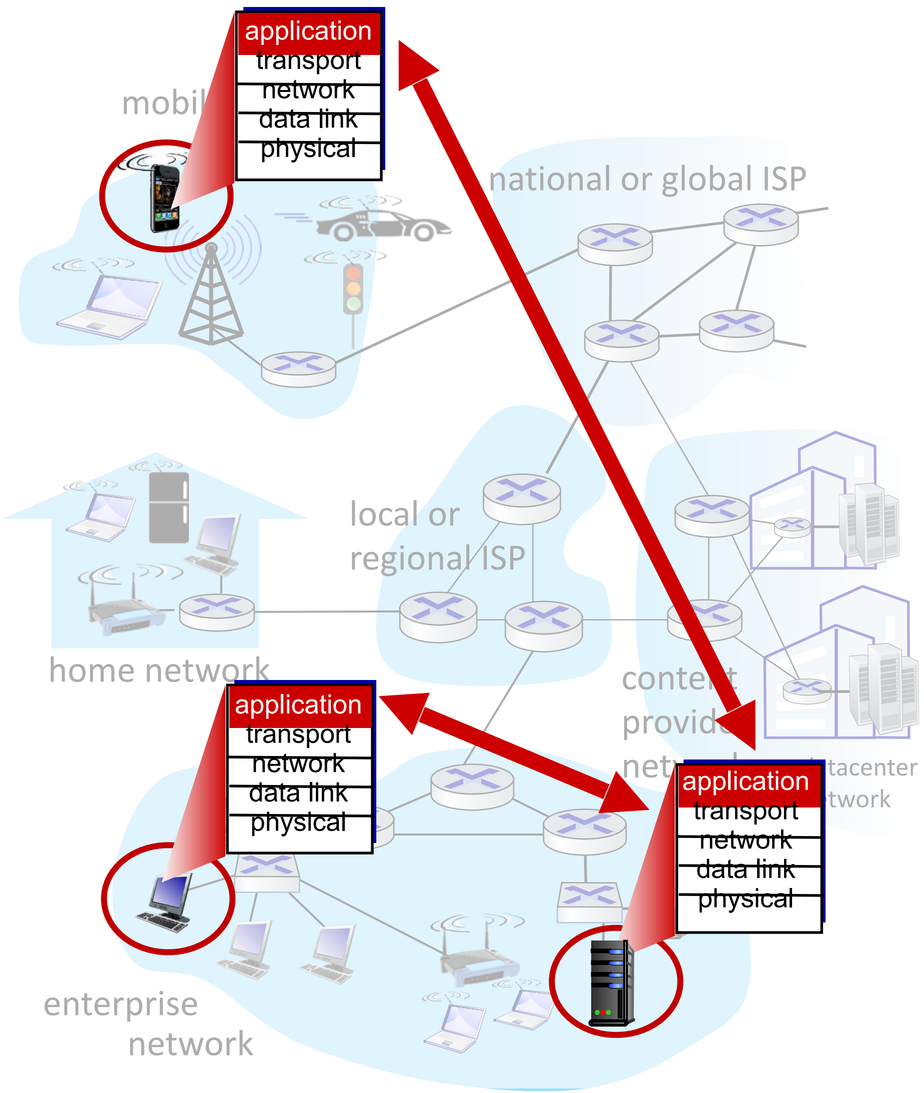

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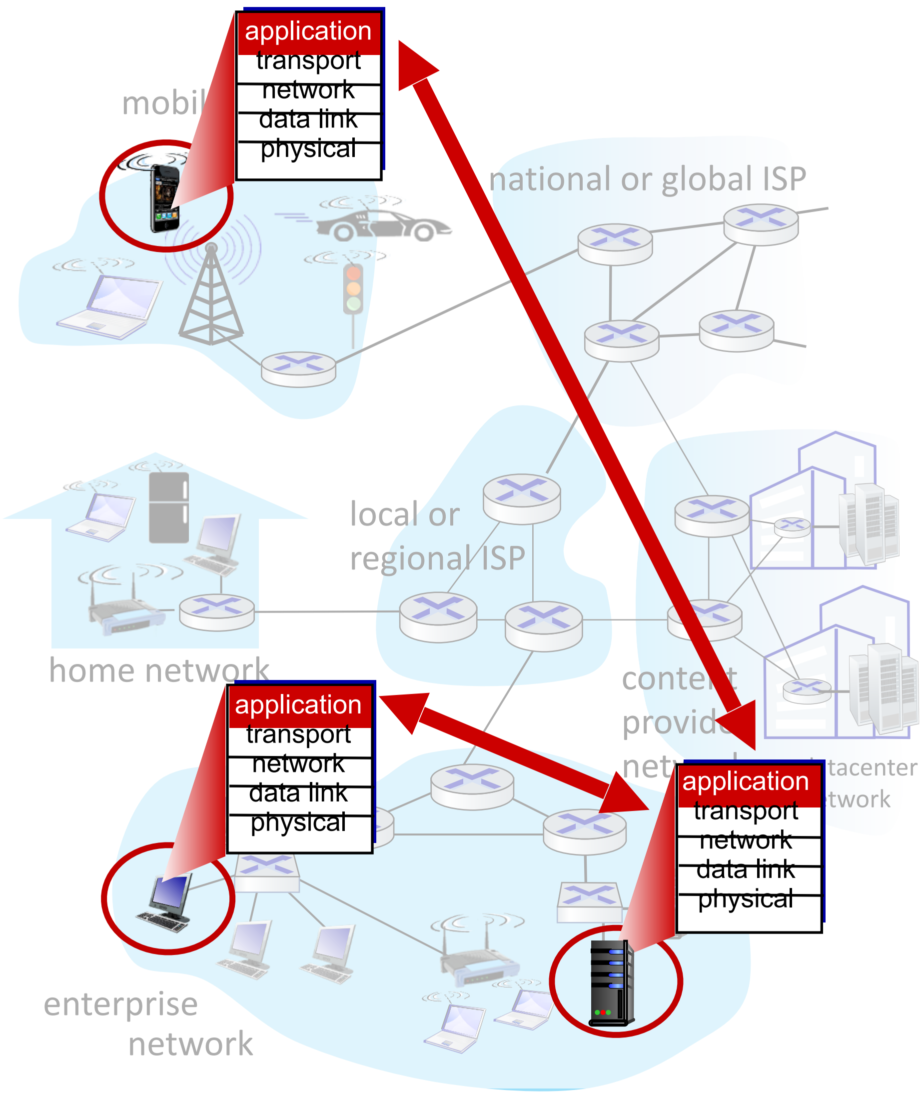
- applications on end systems allows for rapid app development, propagation



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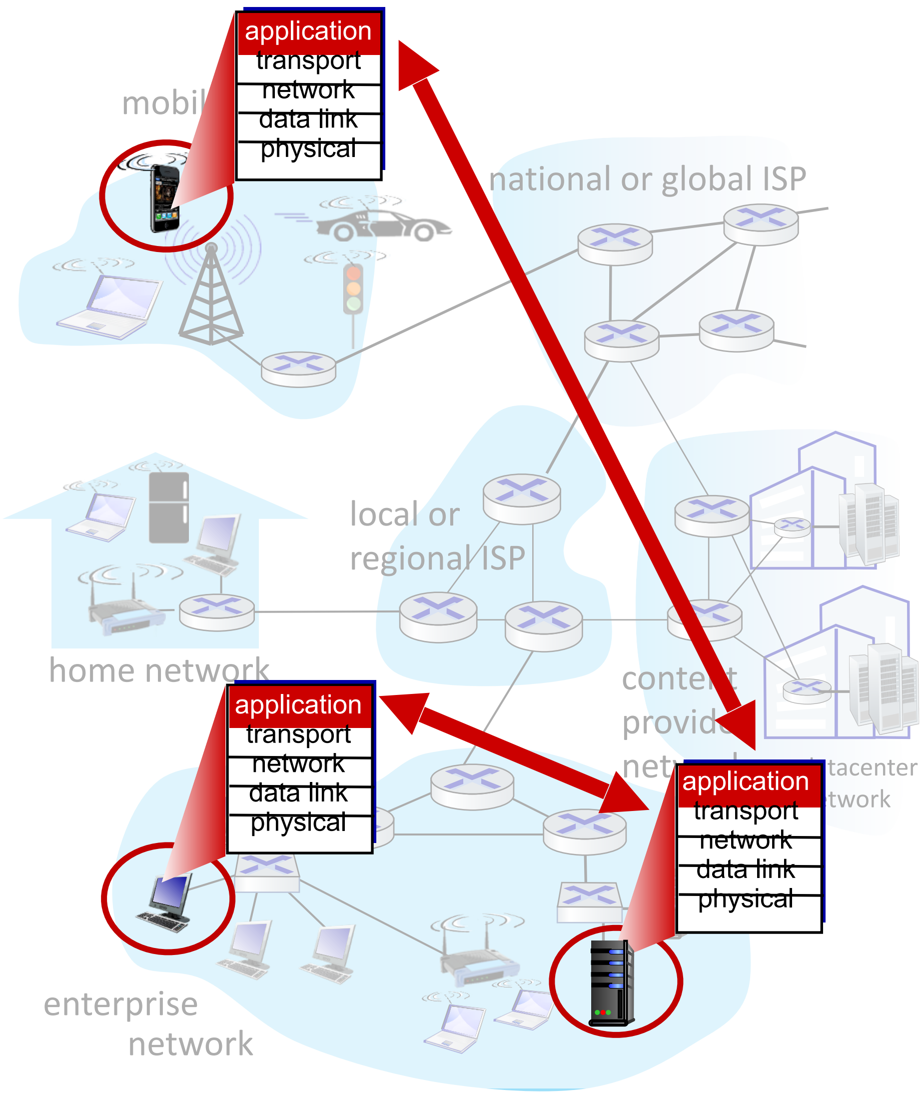
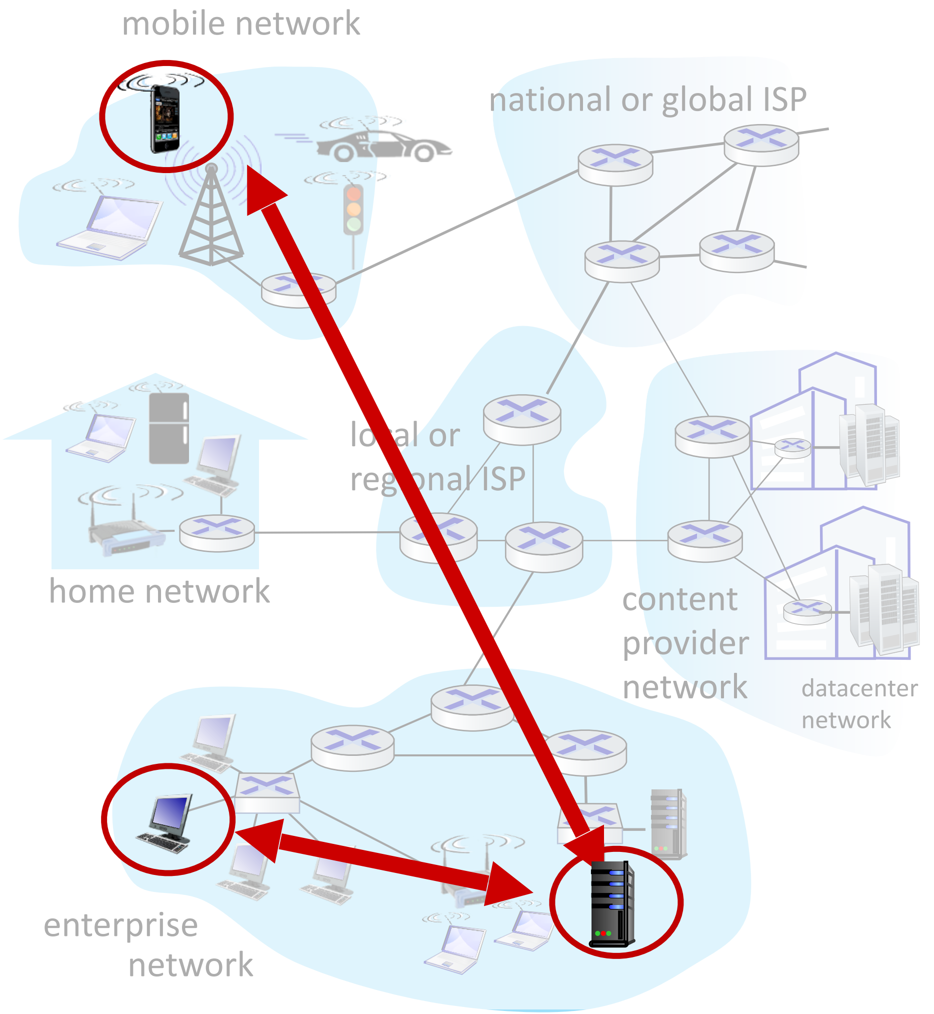


Client-server paradigm

server:



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server:

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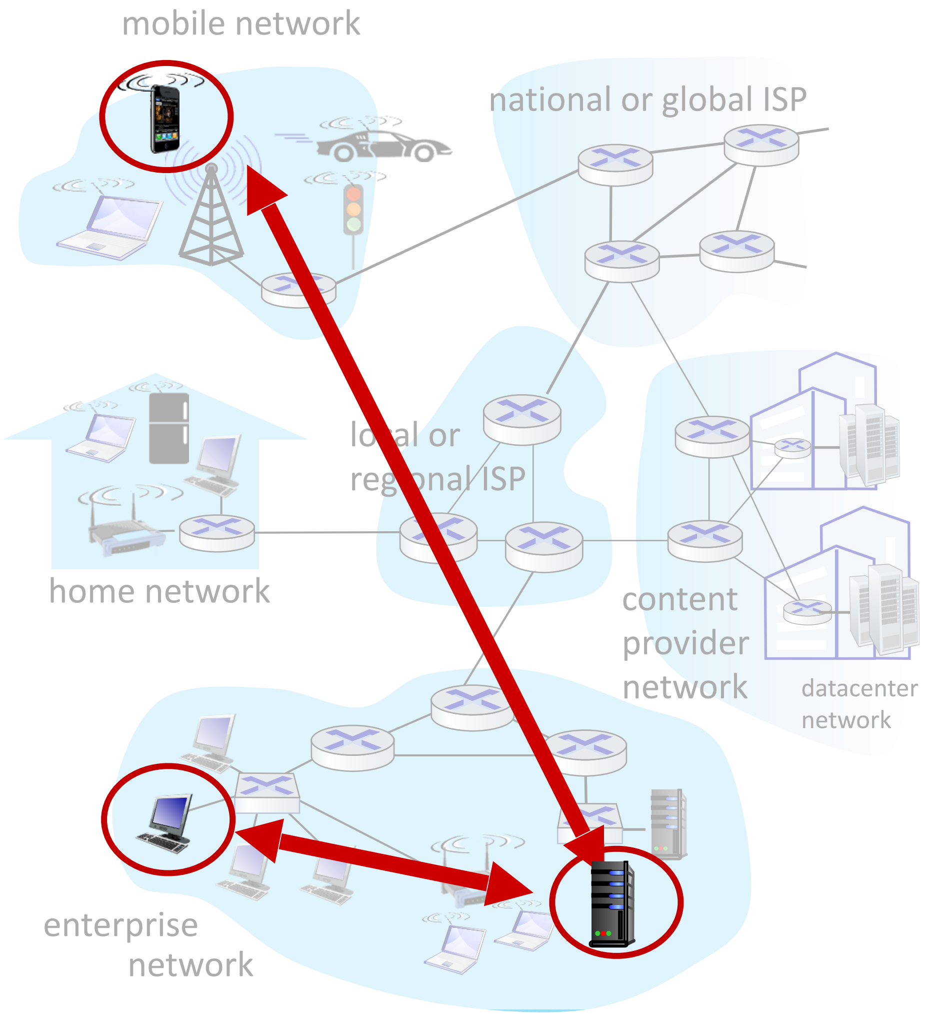
- permanent IP address
- often in data centers, for scaling

clients:



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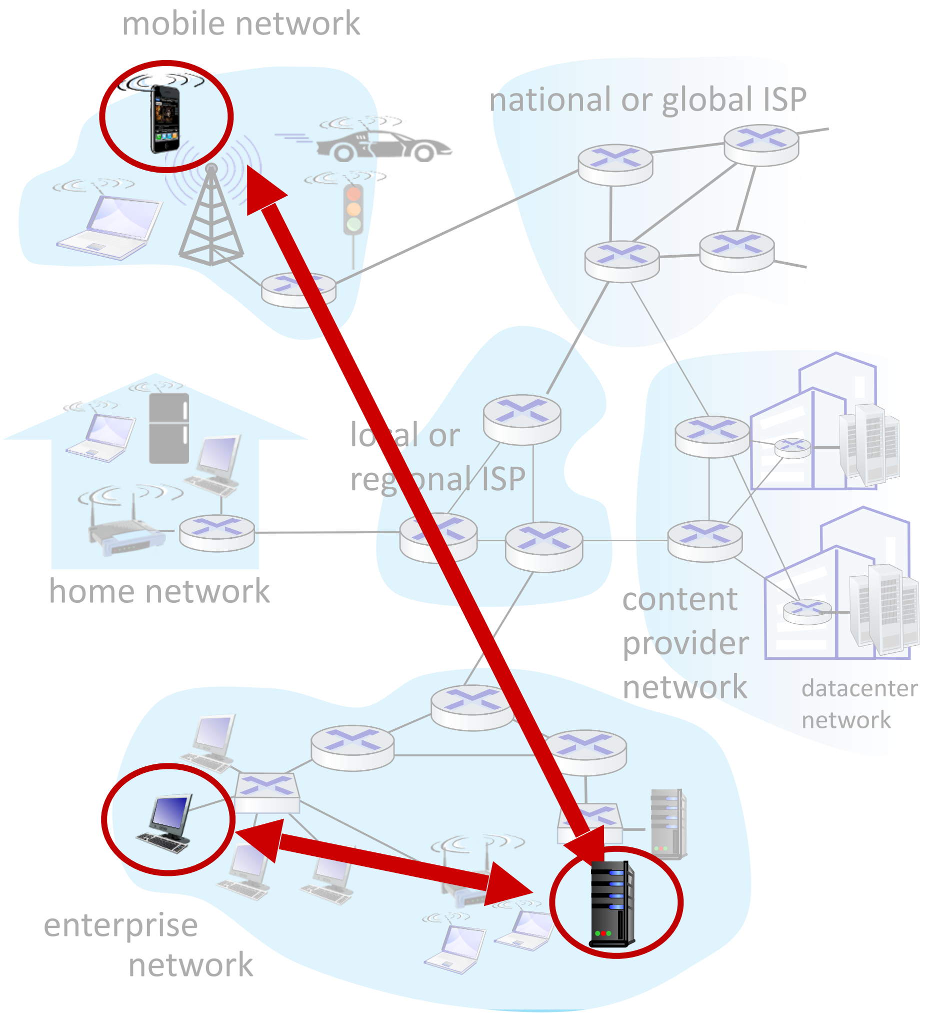
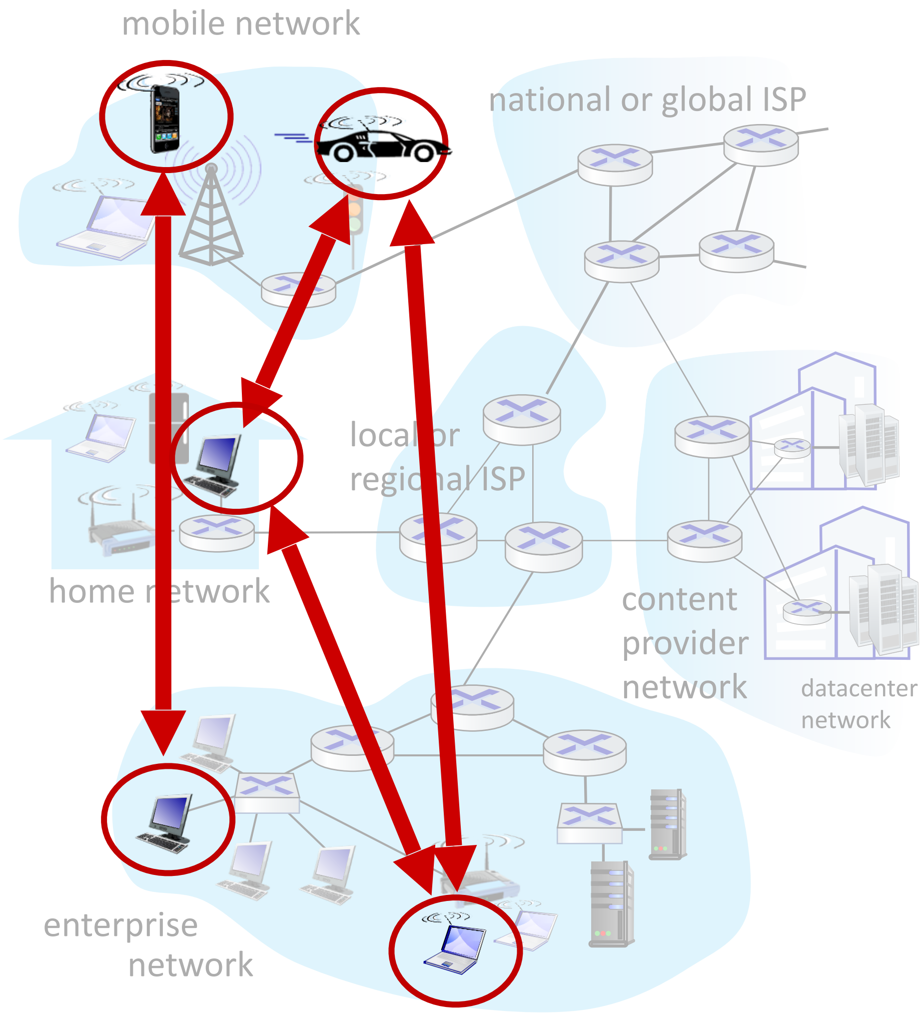
clients:

- contact, communicate with server
- may be intermittently connected
- may have dynamic IP addresses
- do *not* communicate directly with each other

- examples: HTTP, IMAP, FTP



Peer-peer architecture



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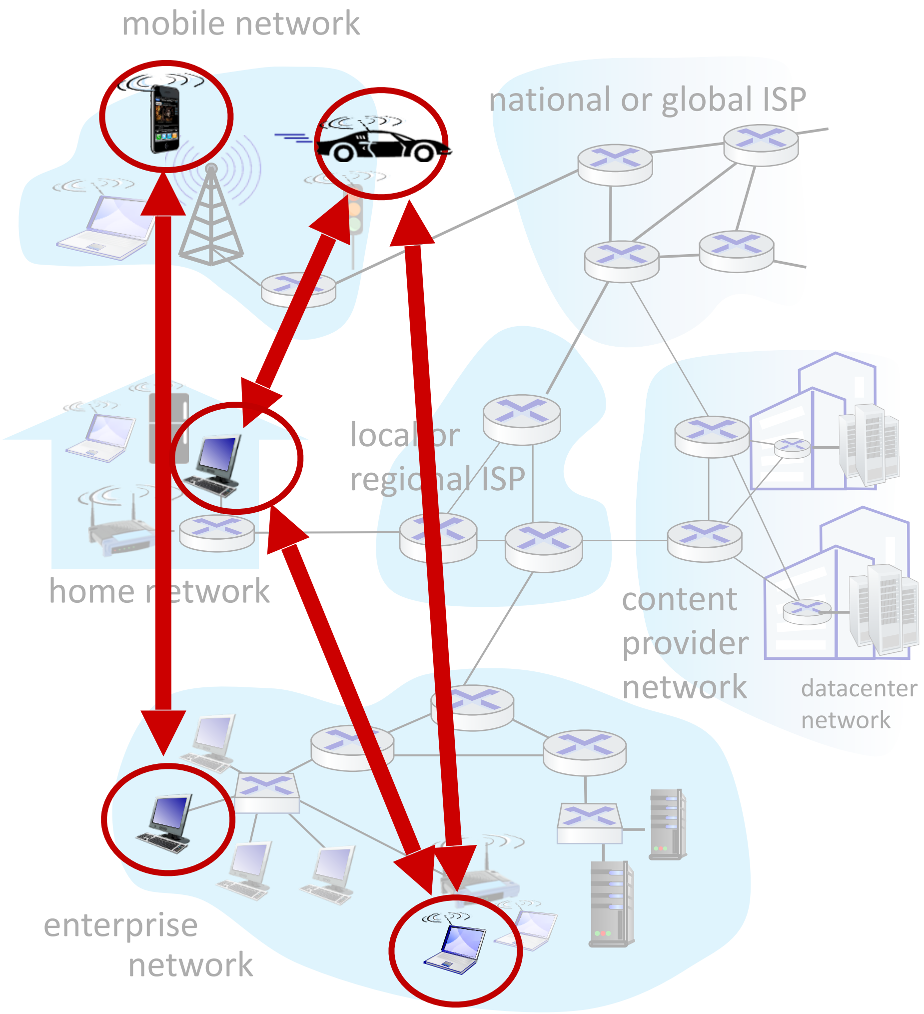

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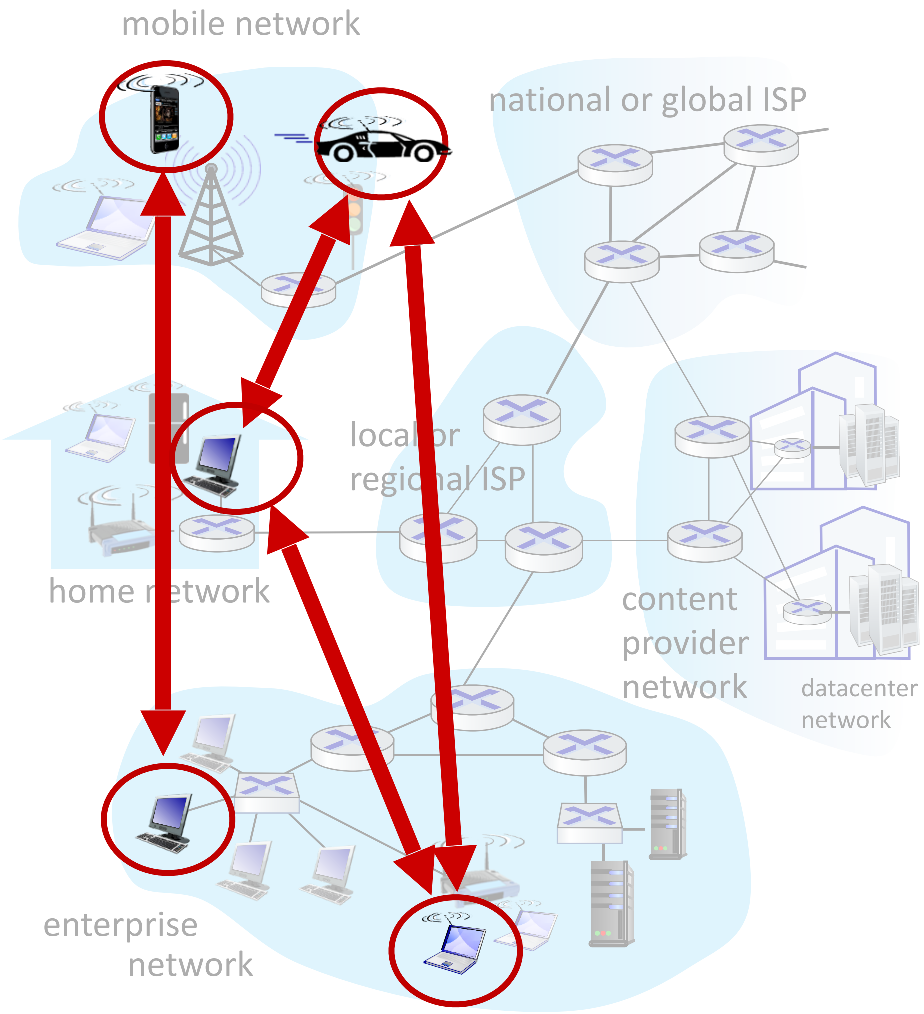

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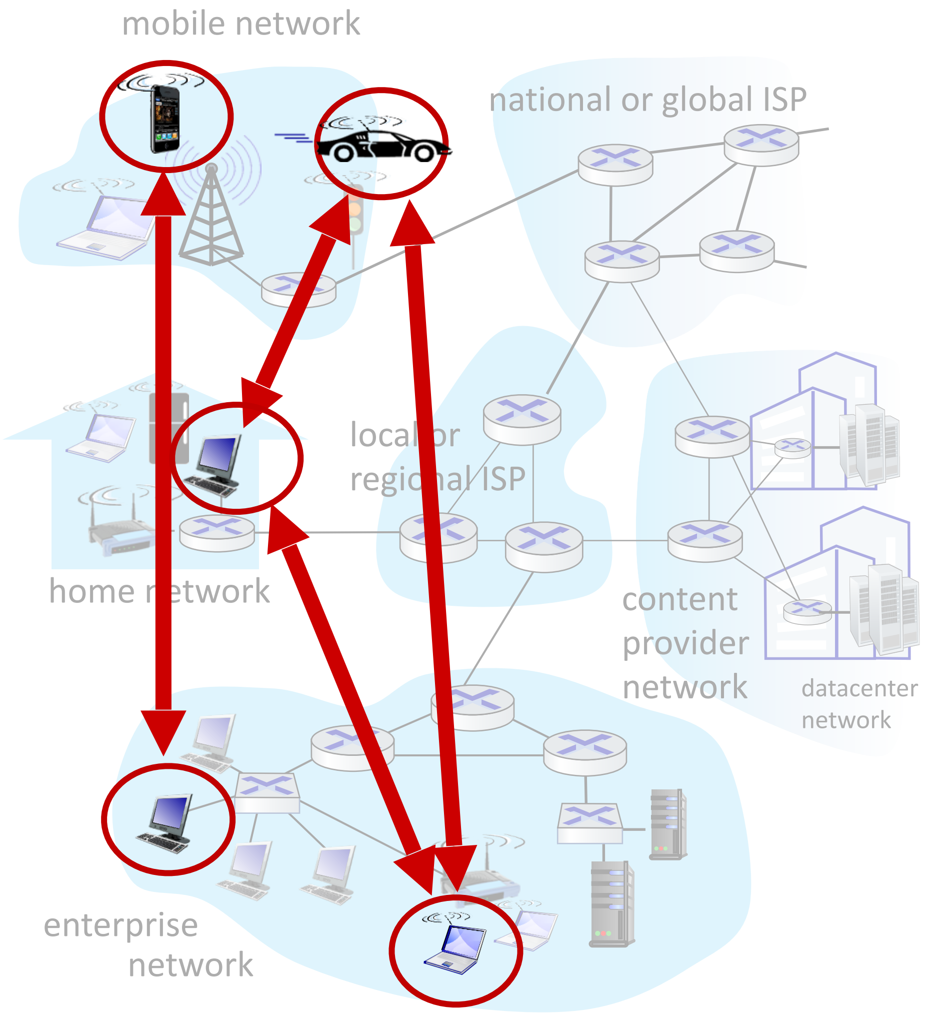

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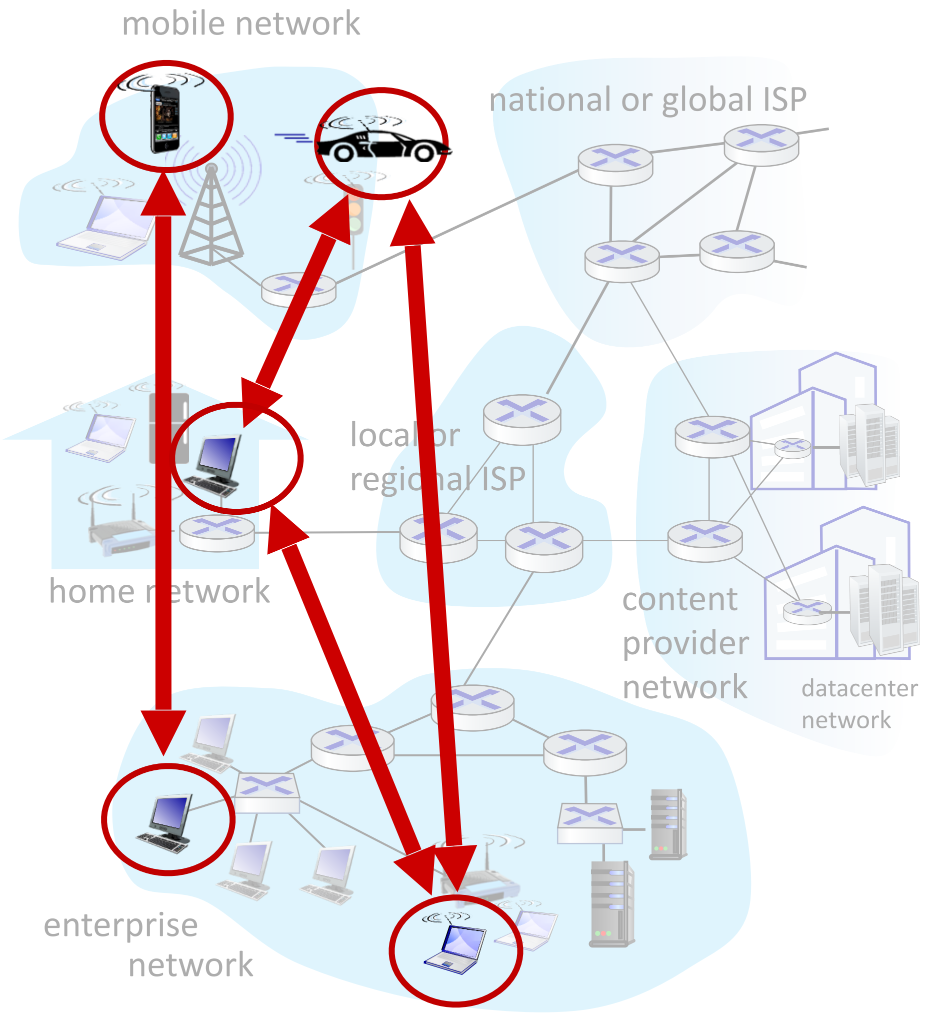

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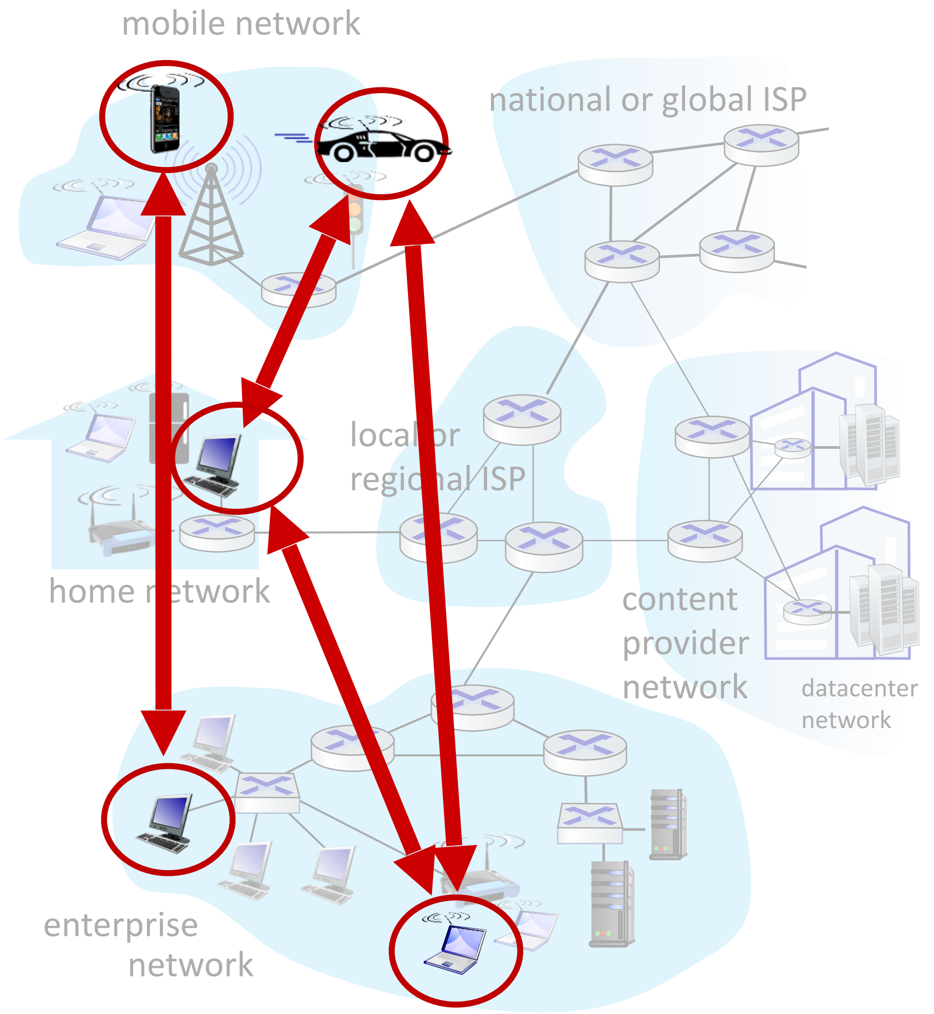
- example: P2P file sharing



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- note: applications with P2P architectures have client processes & server processes

Sockets

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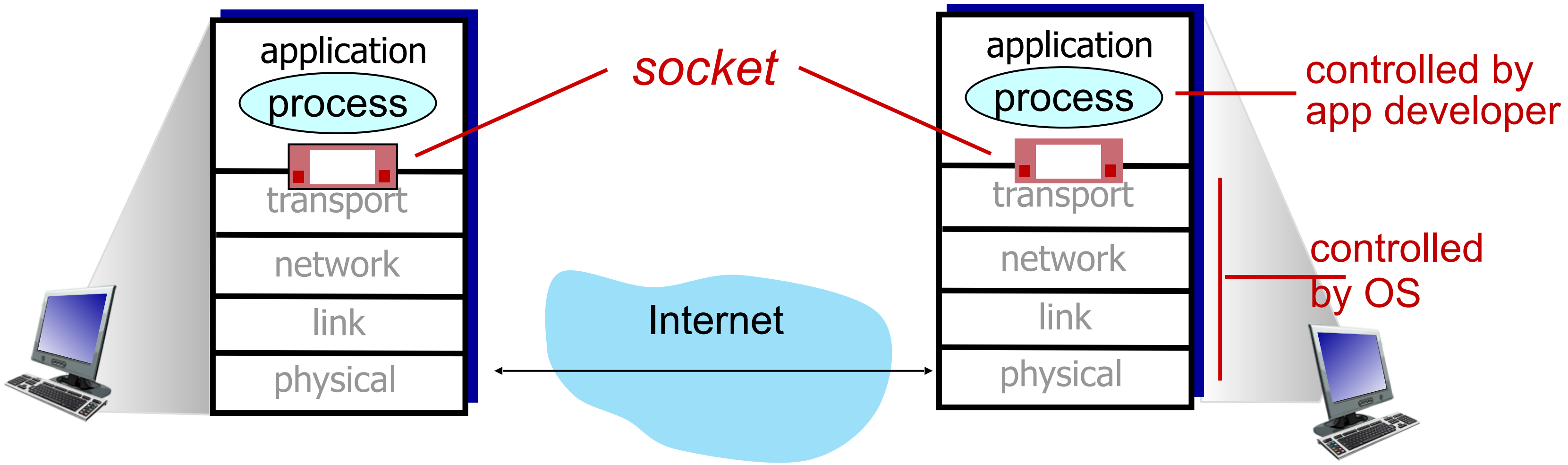

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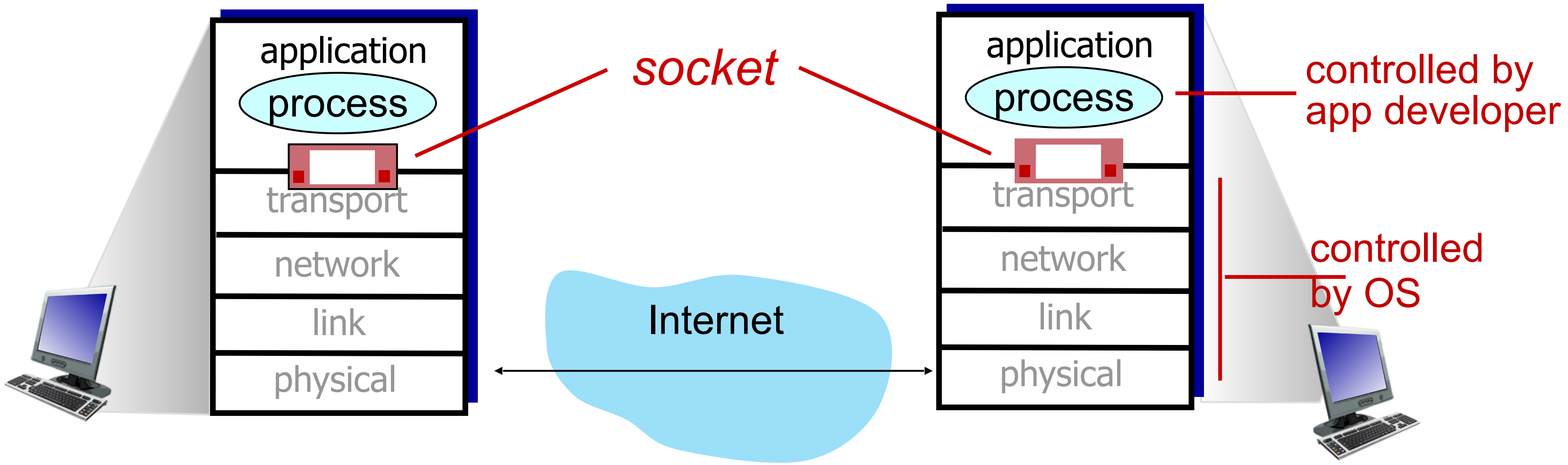

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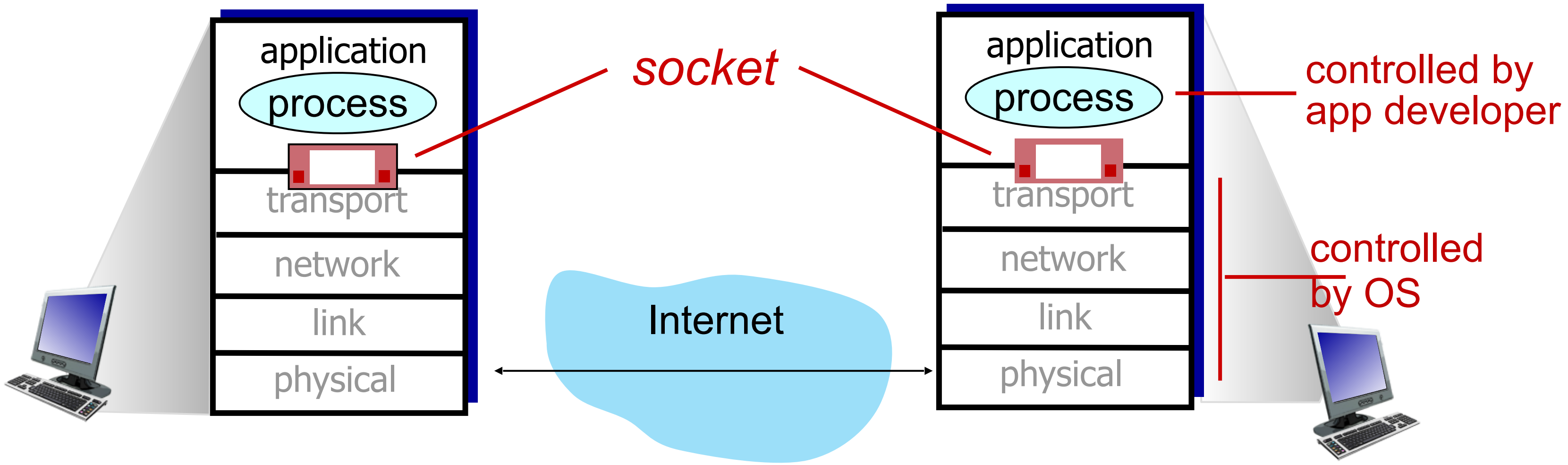

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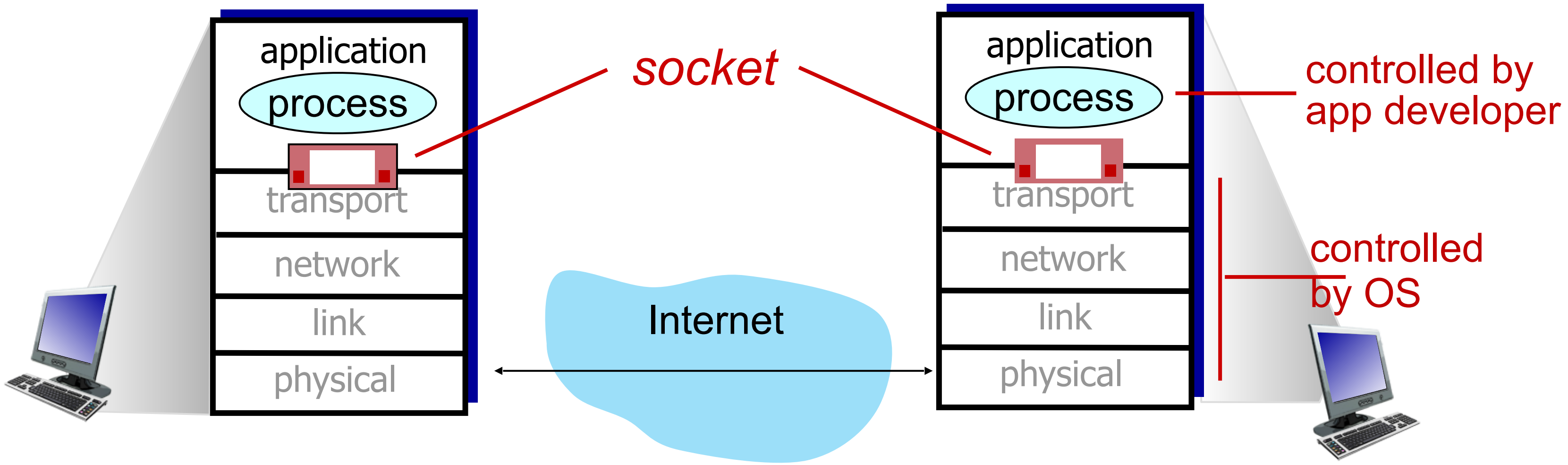

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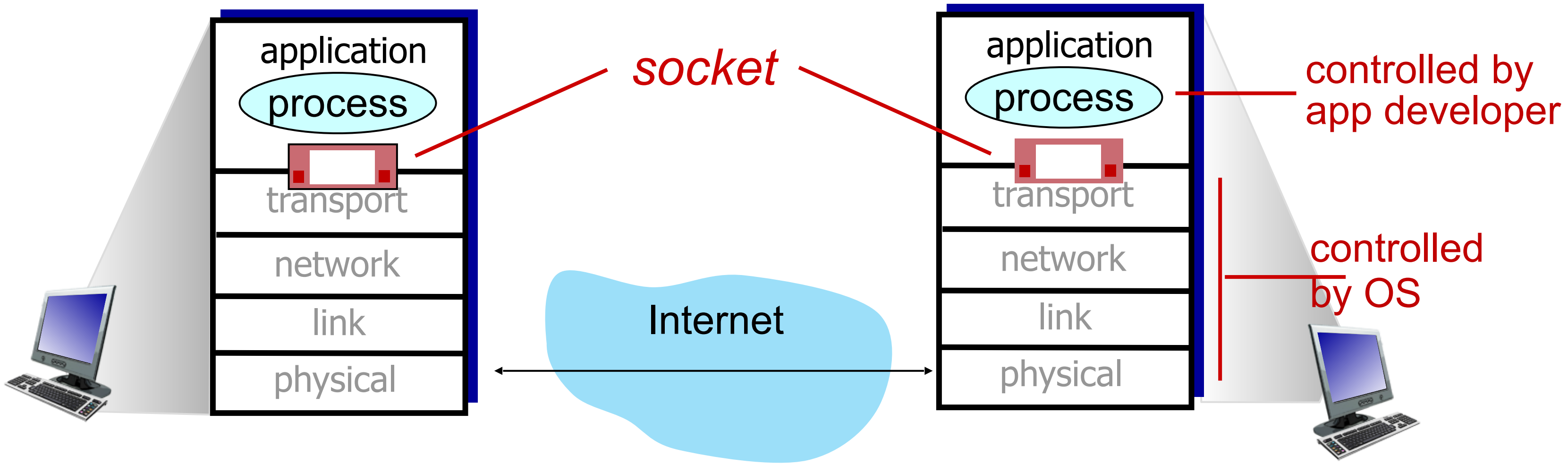

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security

- encryption, data integrity, …

Transport service requirements: common apps

application	data loss	throughput	time sensitive?
file transfer/download	no loss	elastic	no
e-mail	no loss	elastic	no
Web documents	no loss	elastic	no
real-time audio/video	loss-tolerant	audio: 5Kbps-1Mbps video:10Kbps-5Mbps	yes, 10's msec
streaming audio/video	loss-tolerant	same as above	yes, few secs
interactive games	loss-tolerant	Kbps+	yes, 10's msec
text messaging	no loss	elastic	yes and no

Internet transport protocols services

TCP service:

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Internet applications, and transport protocols

application	application layer protocol	transport protocol
file transfer/download	FTP [RFC 959]	TCP
e-mail	SMTP [RFC 5321]	TCP
Web documents	HTTP 1.1 [RFC 7320]	TCP
Internet telephony	SIP [RFC 3261], RTP [RFC 3550], or proprietary	TCP or UDP
streaming audio/video	HTTP [RFC 7320], DASH	TCP
interactive games	WOW, FPS (proprietary)	UDP or TCP

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TLS implemented in application layer

- apps use TLS libraries, that use TCP in turn
- cleartext sent into "socket" traverse Internet *encrypted*
- more: Chapter 8

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Web and HTTP

First, a quick review…

- web page consists of *objects,* each of which can be stored on different Web servers
- object can be HTML file, JPEG image, Java applet, audio file,…
- web page consists of *base HTML-file* which includes *several referenced objects, each* addressable by a *URL,* e.g.,

$$\underbrace{\texttt{www.someschool.edu}}_{\text{host name}}\underbrace{\texttt{/someDept/pic.gif}}_{\text{path name}}$$

HTTP overview

HTTP: hypertext transfer protocol

- Web's application-layer protocol
- client/server model:
  - *client:* browser that requests, receives, (using HTTP protocol) and "displays" Web objects
  - *server:* Web server sends (using HTTP protocol) objects in response to requests

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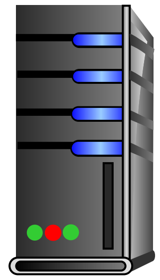
PC running Firefox browser

iPhone running Safari browser



server running Apache Web server

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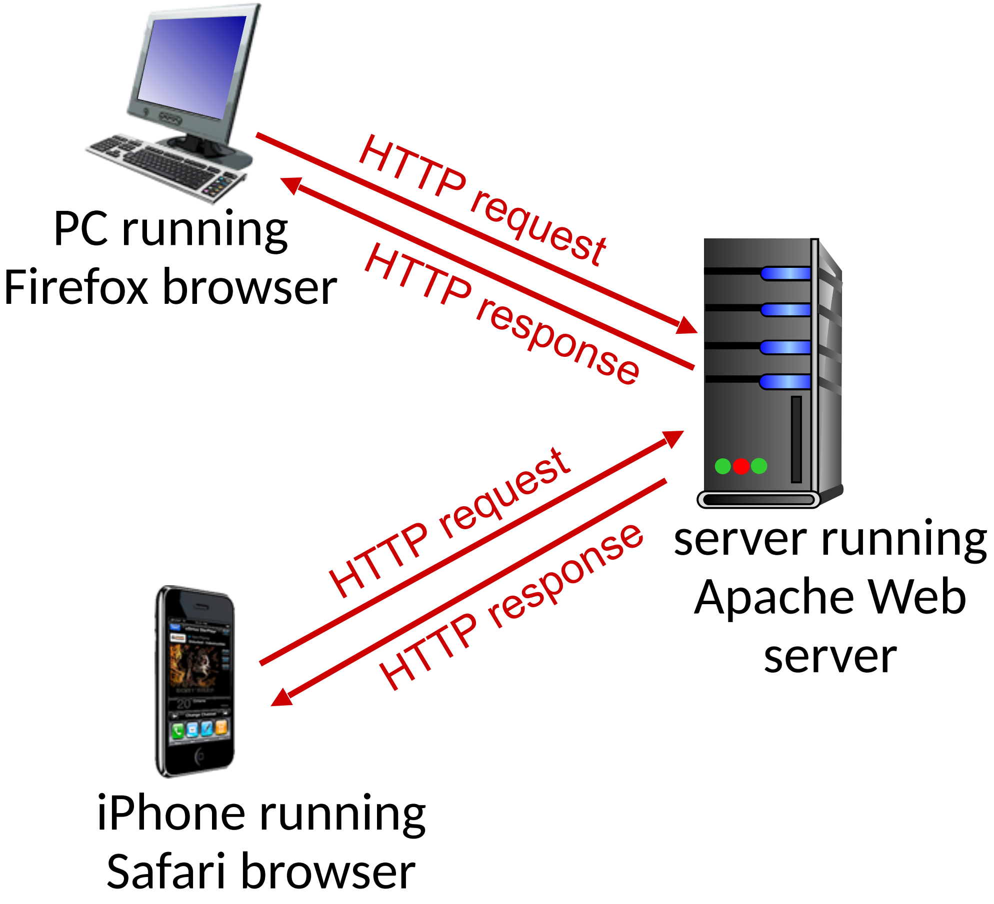

HTTP overview (continued)

HTTP uses TCP:

- client initiates TCP connection (creates socket) to server, port 80
- server accepts TCP connection from client
- HTTP messages (application-layer protocol messages) exchanged between browser (HTTP client) and Web server (HTTP server)
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aside

protocols that maintain "state" are complex!

- past history (state) must be maintained
- if server/client crashes, their views of "state" may be inconsistent, must be reconciled

HTTP connections: two types

Non-persistent HTTP

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2. at most one object sent over TCP connection
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Non-persistent HTTP: example

User enters URL: **`www.someSchool.edu/someDepartment/home.index`**
(containing text, references to 10 jpeg images)

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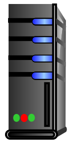
1a. HTTP client initiates TCP connection to HTTP server (process) at www.someSchool.edu on port 80



1b. HTTP server at host www.someSchool.edu waiting for TCP connection at port 80 "accepts" connection, notifying client

time

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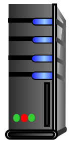

1b. HTTP server at host www.someSchool.edu waiting for TCP connection at port 80 "accepts" connection, notifying client

2. HTTP client sends HTTP *request message* (containing URL) into TCP connection socket. Message indicates that client wants object someDepartment/home.index

3. HTTP server receives request message, forms *response message* containing requested object, and sends message into its socket

time

Non-persistent HTTP: example (cont.)

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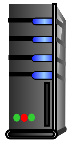

4. HTTP server closes TCP connection.

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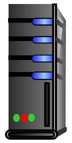

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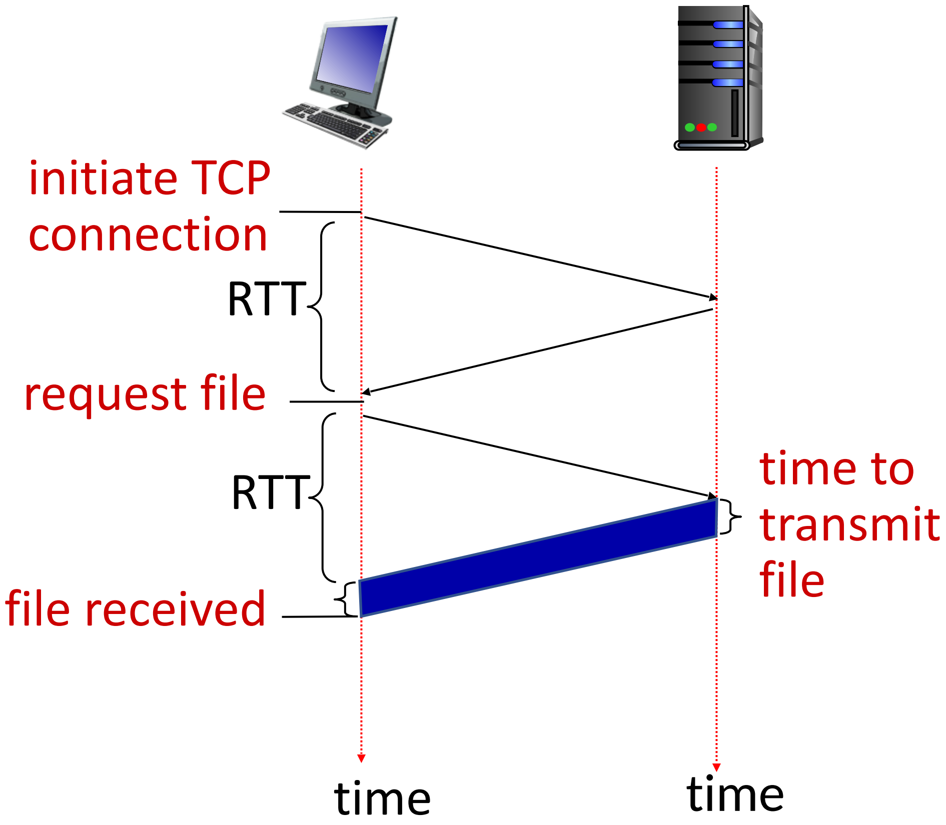
6. Steps 1-5 repeated for each of 10 jpeg objects

time

Non-persistent HTTP: response time

RTT (definition): time for a small packet to travel from client to server and back



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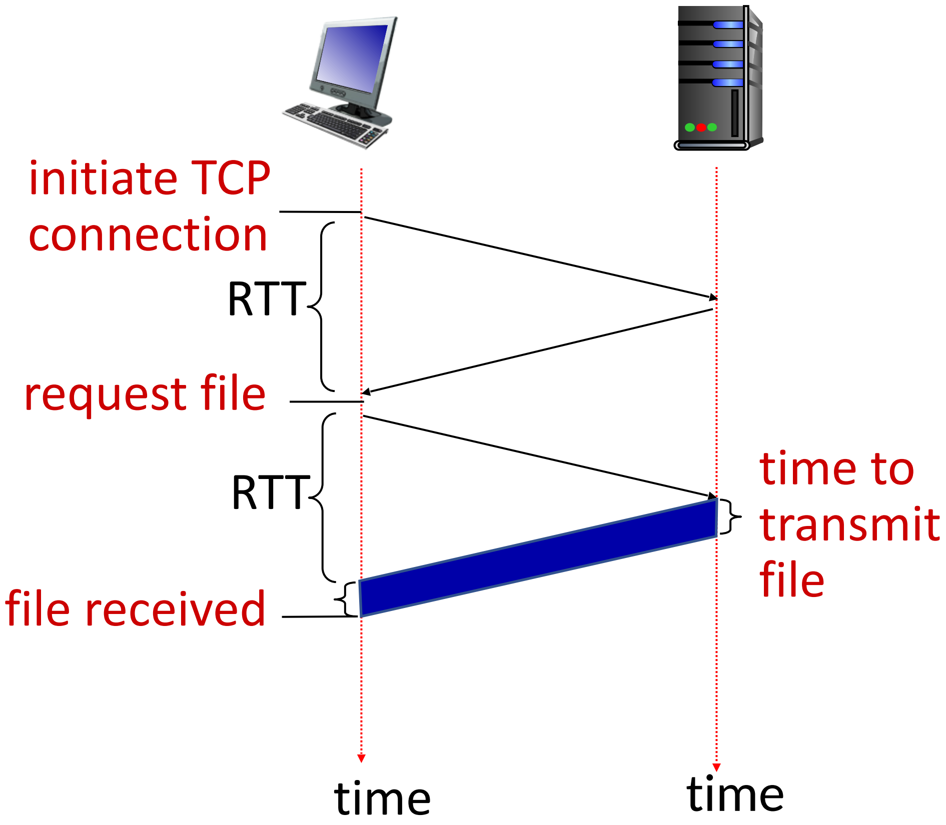

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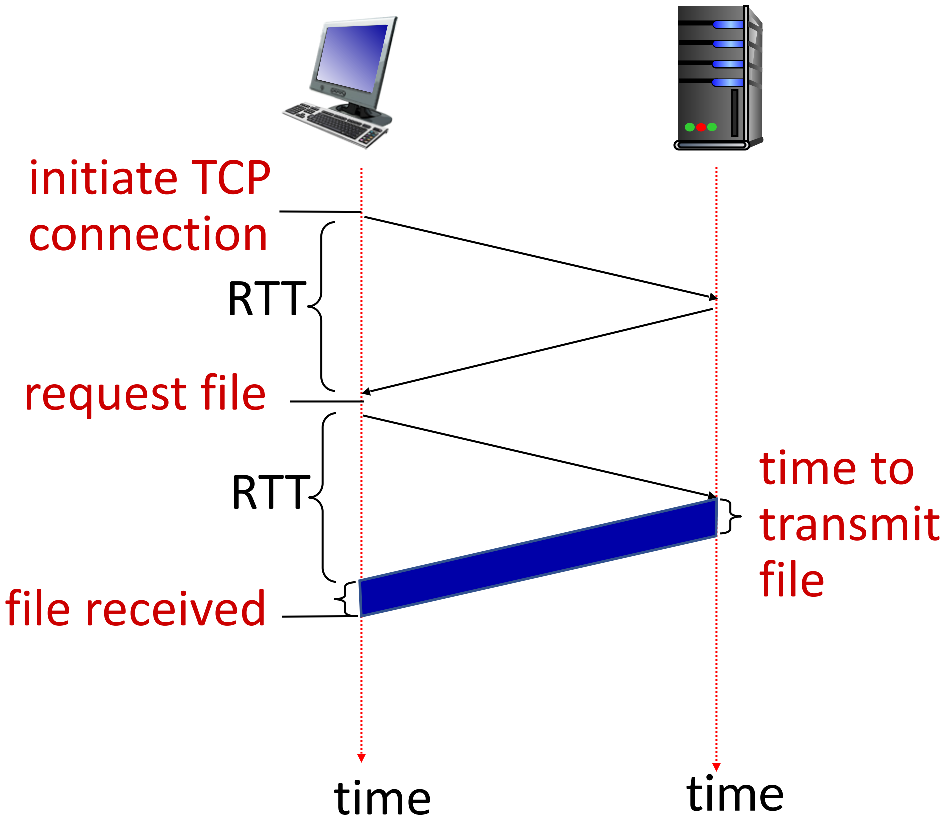

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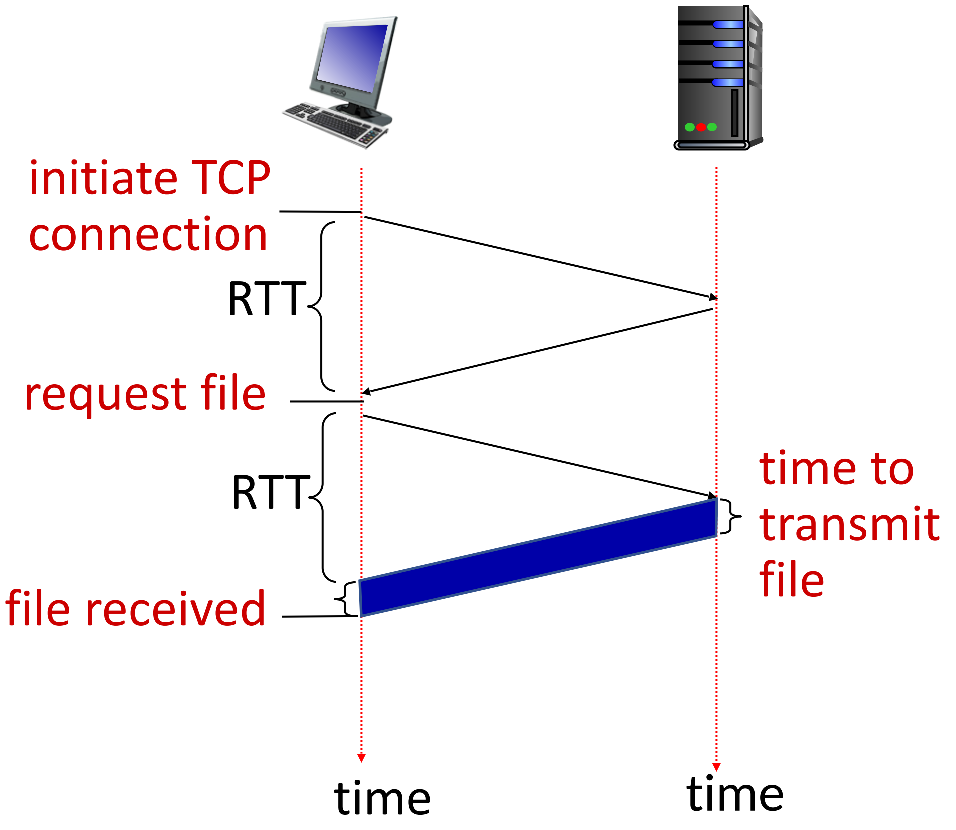

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Persistent HTTP (HTTP 1.1)

Non-persistent HTTP issues:

- requires 2 RTTs per object
- OS overhead for *each* TCP connection
- browsers often open multiple parallel TCP connections to fetch referenced objects in parallel

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Persistent HTTP (HTTP1.1):

- server leaves connection open after sending response
- subsequent HTTP messages between same client/server sent over open connection
- client sends requests as soon as it encounters a referenced object
- as little as one RTT for all the referenced objects (cutting response time in half)

HTTP request message

- two types of HTTP messages: *request, response*
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  - ASCII (human-readable format)

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carriage return character

line-feed character

request line (GET, POST, HEAD commands)

```
GET /index.html HTTP/1.1\r\n
```

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- HTTP request message:
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carriage return character

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request line (GET, POST, HEAD commands)

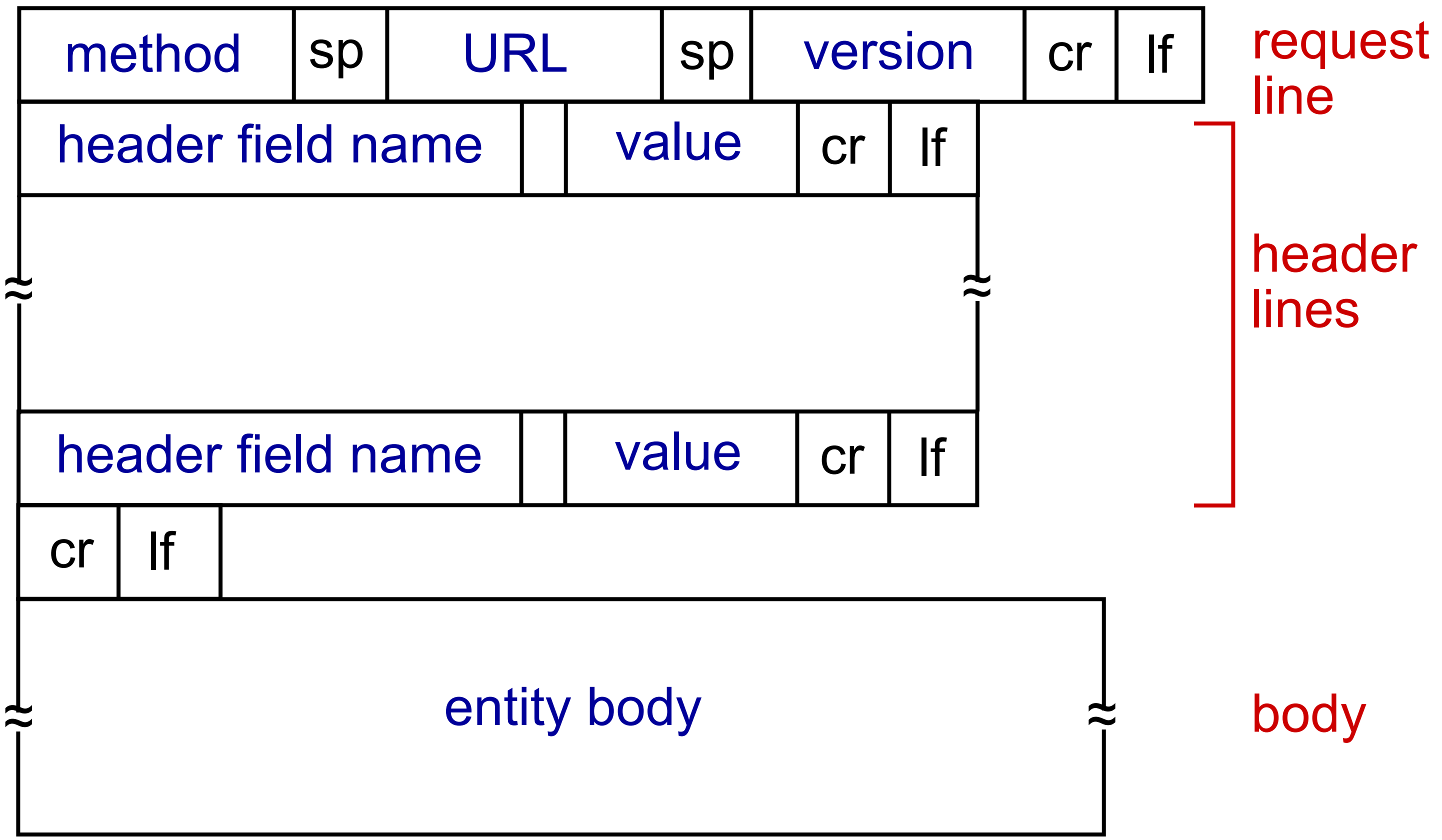
```
GET /index.html HTTP/1.1\r\n
Host: www-net.cs.umass.edu\r\n
User-Agent: Mozilla/5.0 (Macintosh; Intel Mac OS X
   10.15; rv:80.0) Gecko/20100101 Firefox/80.0 \r\n
Accept: text/html,application/xhtml+xml\r\n
Accept-Language: en-us,en;q=0.5\r\n
Accept-Encoding: gzip,deflate\r\n
Connection: keep-alive\r\n
\r\n
```

header lines

carriage return, line feed at start of line indicates end of header lines

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

HTTP request message: general format



Other HTTP request messages

POST method:

- web page often includes form input
- user input sent from client to server in entity body of HTTP POST request message

GET method (for sending data to server):

- include user data in URL field of HTTP GET request message (following a ‘?’):

```
www.somesite.com/animalsearch?monkeys&banana
```

Other HTTP request messages

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- include user data in URL field of HTTP GET request message (following a ‘?’):

```
www.somesite.com/animalsearch?monkeys&banana
```

HEAD method:

- requests headers (only) that would be returned *if* specified URL were requested with an HTTP GET method.

PUT method:

- uploads new file (object) to server
- completely replaces file that exists at specified URL with content in entity body of POST HTTP request message

HTTP response message

status line (protocol status code status phrase)

```
HTTP/1.1 200 OK
```

HTTP response message

status line (protocol
status code status phrase)

header
lines

```
HTTP/1.1 200 OK
Date: Tue, 08 Sep 2020 00:53:20 GMT
Server: Apache/2.4.6 (CentOS) OpenSSL/
   1.0.2k-fips PHP/7.4.9 mod_perl/2.0.11
   Perl/v5.16.3
Last-Modified: Tue, 01 Mar 2016 18:57:50 GMT
ETag: "a5b-52d015789ee9e"
Accept-Ranges: bytes
Content-Length: 2651
Content-Type: text/html; charset=UTF-8
\r\n
```

HTTP response message

status line (protocol status code status phrase)

```
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Server: Apache/2.4.6 (CentOS) OpenSSL/
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ETag: "a5b-52d015789ee9e"
Accept-Ranges: bytes
Content-Length: 2651
Content-Type: text/html; charset=UTF-8
\r\n
data data data data data ...
```

header lines

data, e.g., requested HTML file

HTTP response status codes

- status code appears in 1st line in server-to-client response message.
- some sample codes:

200 OK

- request succeeded, requested object later in this message

301 Moved Permanently

- requested object moved, new location specified later in this message (in Location: field)

400 Bad Request

- request msg not understood by server

404 Not Found

- requested document not found on this server

505 HTTP Version Not Supported

Trying out HTTP (client side) for yourself

1. Telnet to your favorite Web server:

% telnet www.isel.pt 80

- opens TCP connection to port 80 (default HTTP server port) at www.isel.pt.
- anything typed in will be sent to port 80 at www.isel.pt

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2. type in a GET HTTP request:

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GET / HTTP/1.1
Host: www.isel.pt
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- by typing this in (hit carriage return twice), you send this minimal (but complete) GET request to HTTP server

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3. look at response message sent by HTTP server!

(or use Wireshark to look at captured HTTP request/response)

HTTP/2

Key goal: decreased delay in multi-object HTTP requests

HTTP1.1: introduced multiple, pipelined GETs over single TCP connection

- server responds *in-order* (FCFS: first-come-first-served scheduling) to GET requests
- with FCFS, small object may have to wait for transmission (head-of-line (HOL) blocking) behind large object(s)
- loss recovery (retransmitting lost TCP segments) stalls object transmission

HTTP/2

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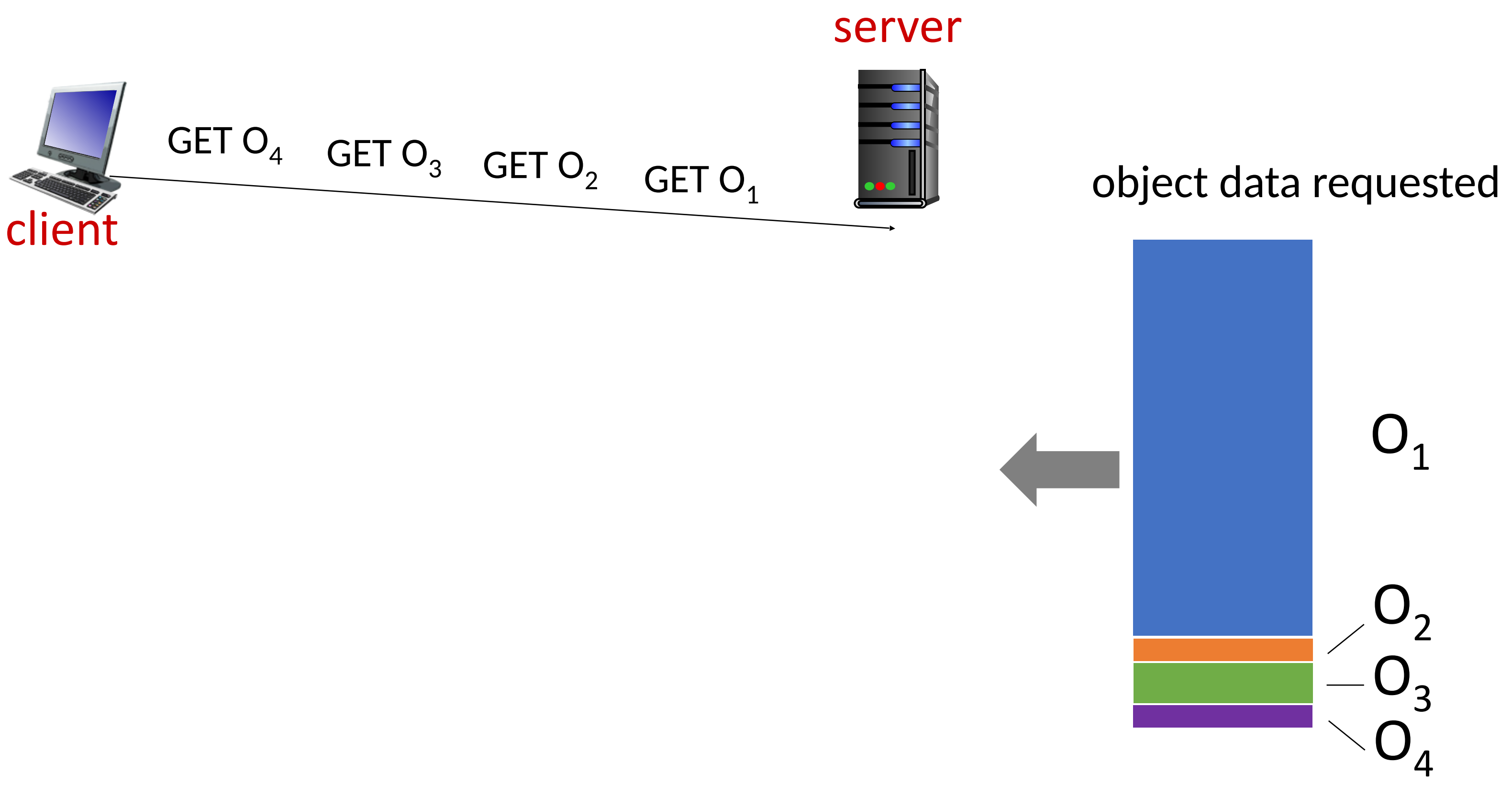
HTTP/2: [RFC 7540, 2015] increased flexibility at *server* in sending objects to client:

- methods, status codes, most header fields unchanged from HTTP 1.1
- transmission order of requested objects based on client-specified object priority (not necessarily FCFS)
- *push* unrequested objects to client
- divide objects into frames, schedule frames to mitigate HOL blocking

HTTP/2: mitigating HOL blocking

HTTP 1.1: client requests 1 large object (e.g., video file) and 3 smaller objects



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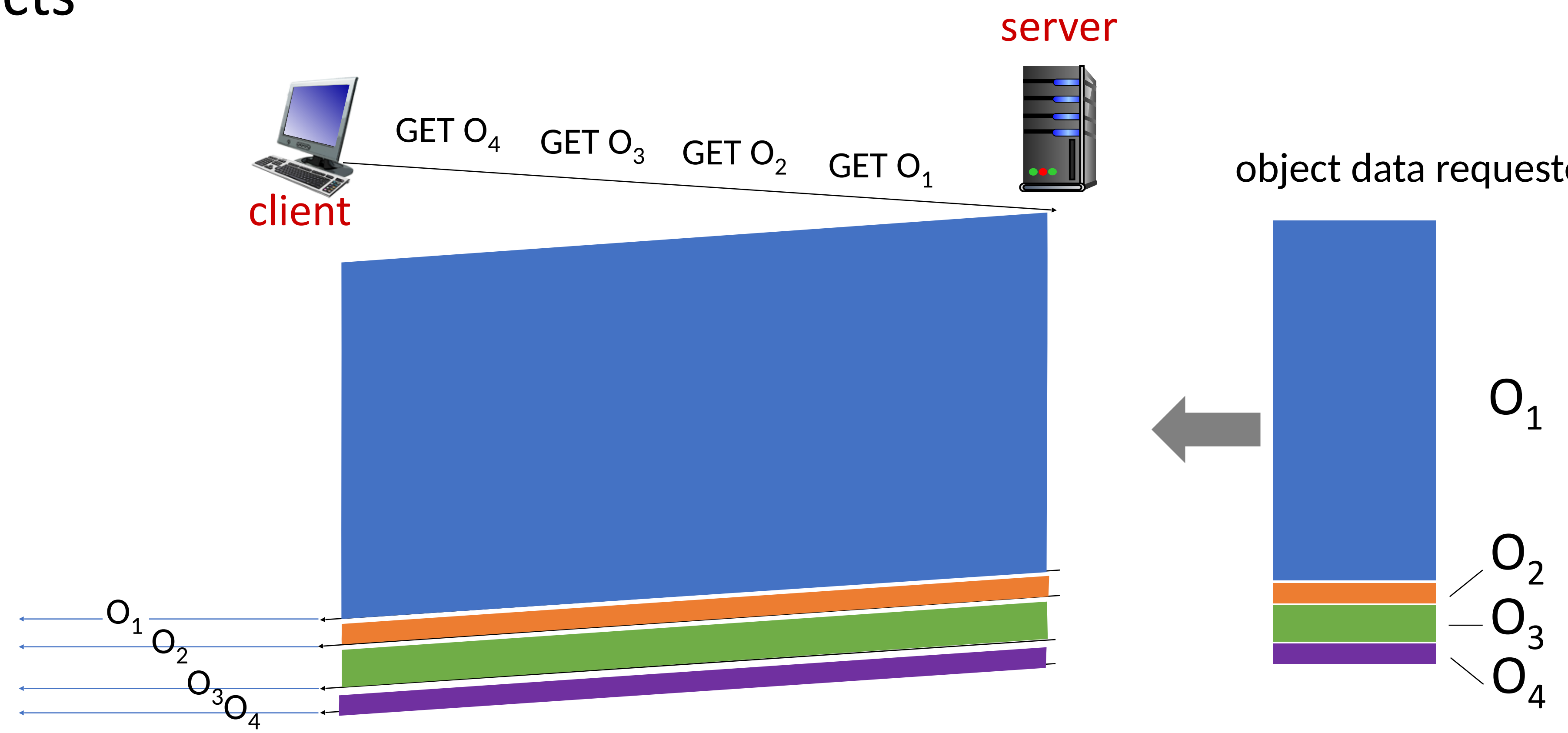

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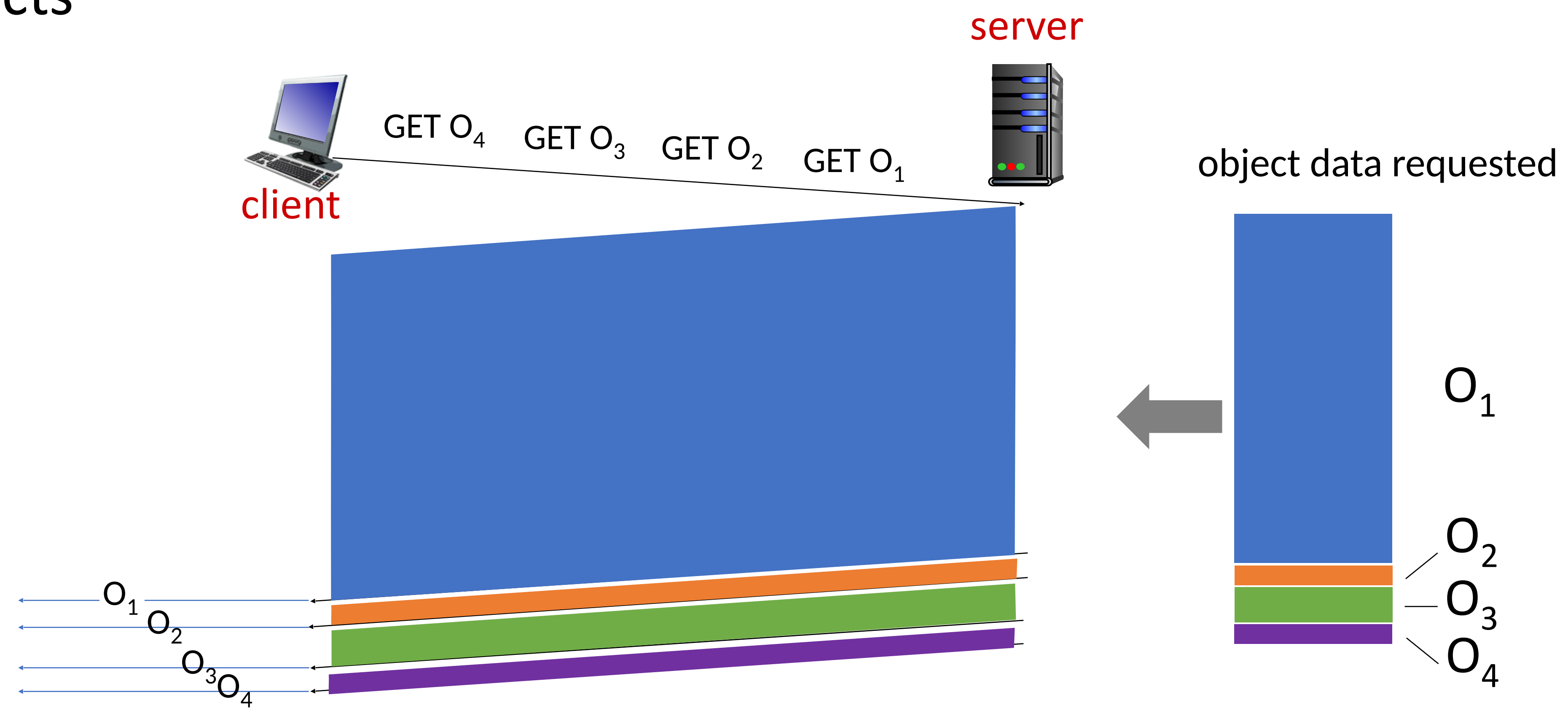
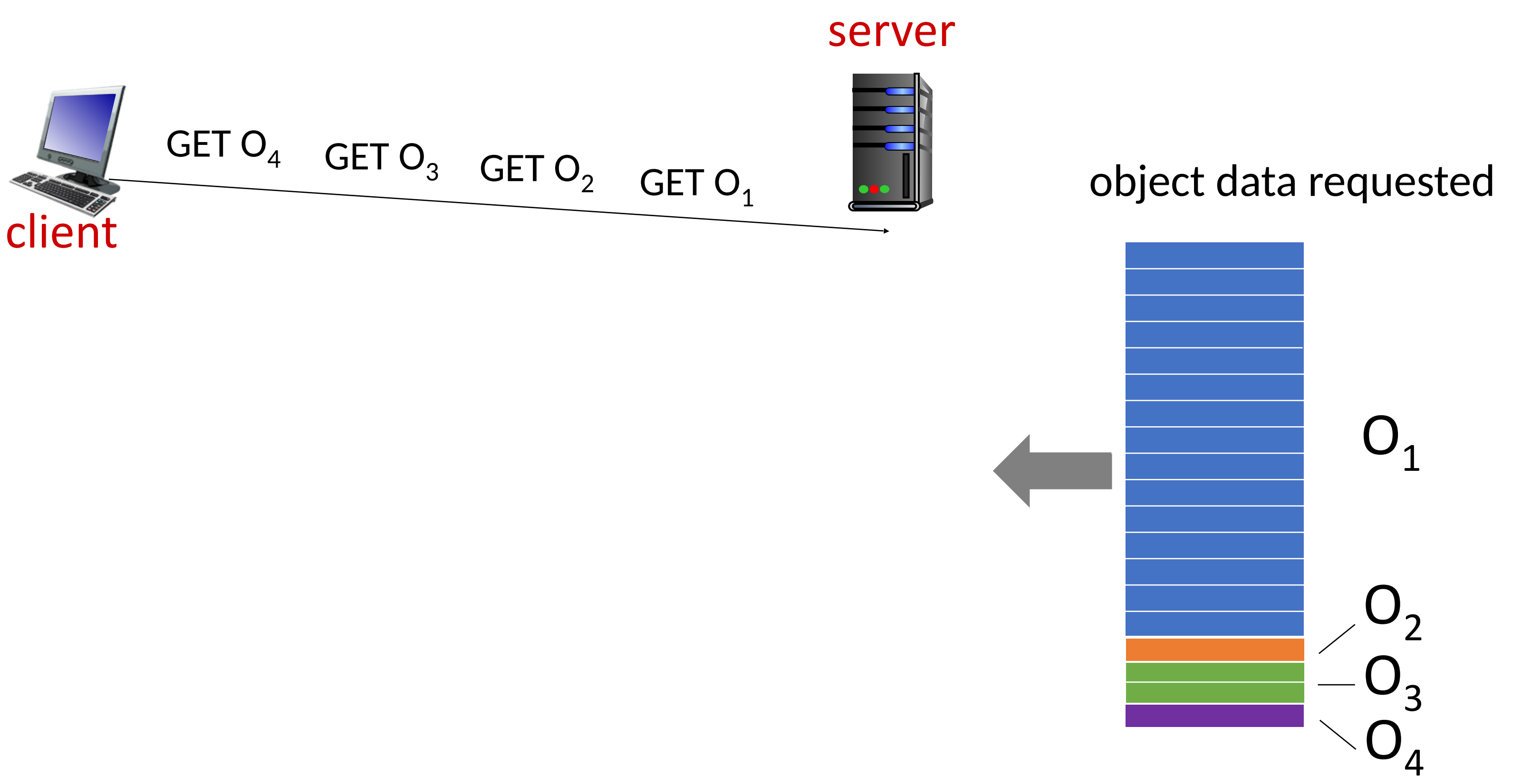


objects delivered in order requested: O_2, O_3, O_4 wait behind O_1

HTTP/2: mitigating HOL blocking

HTTP/2: objects divided into frames, frame transmission interleaved



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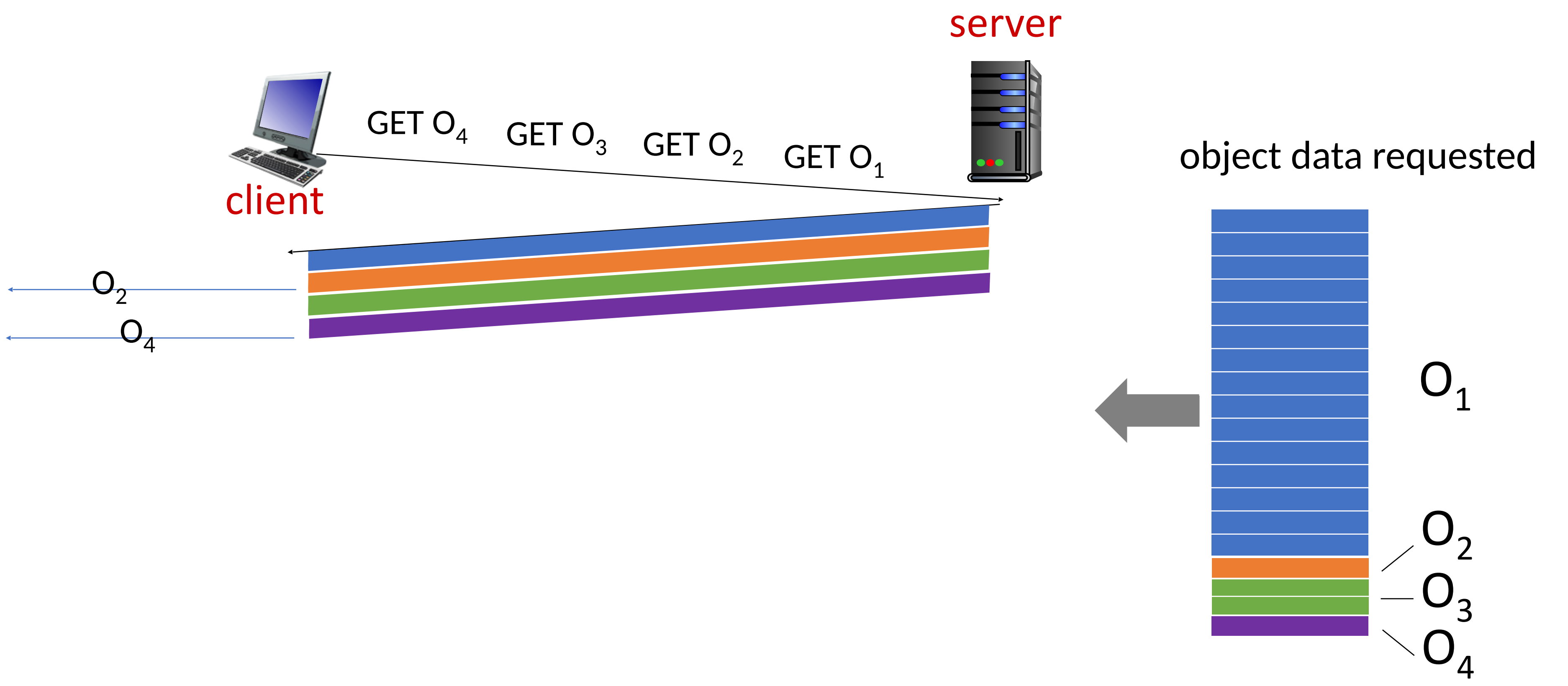

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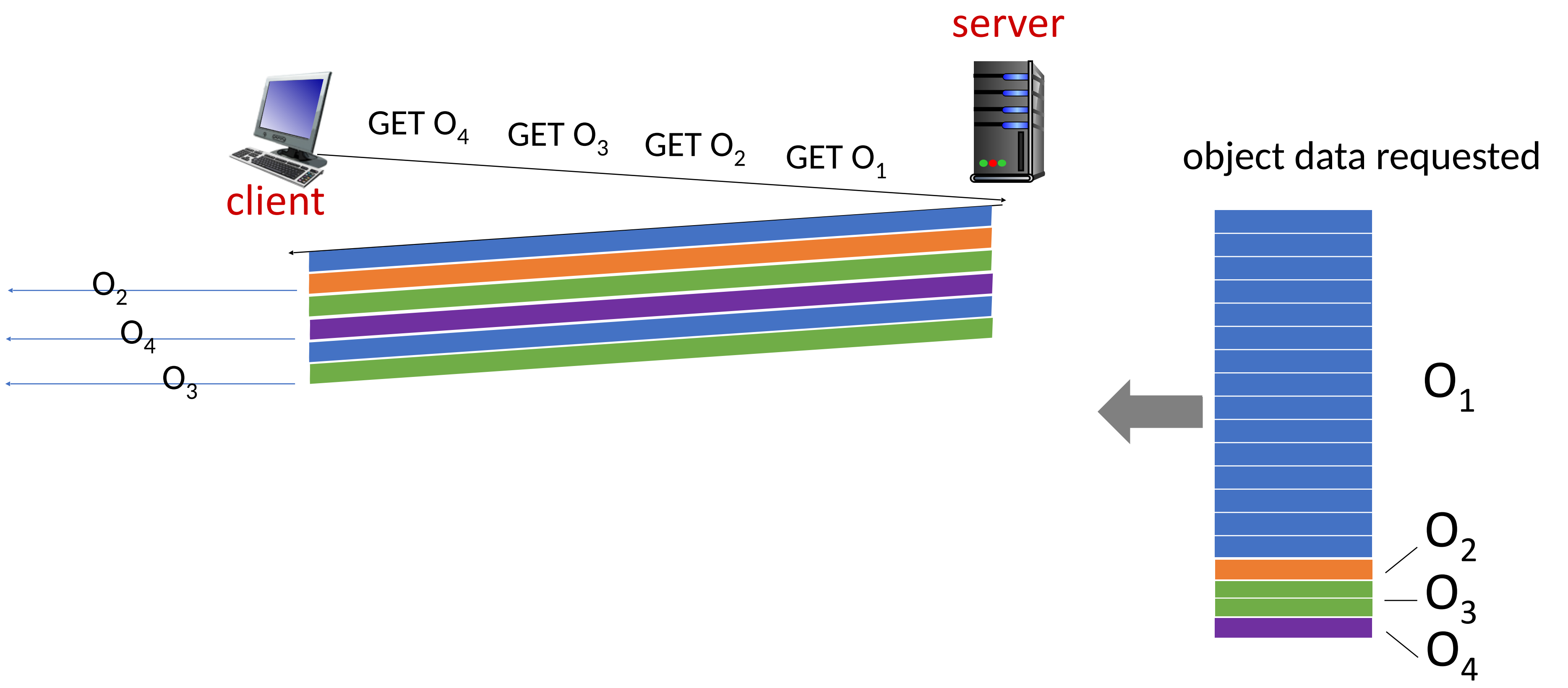

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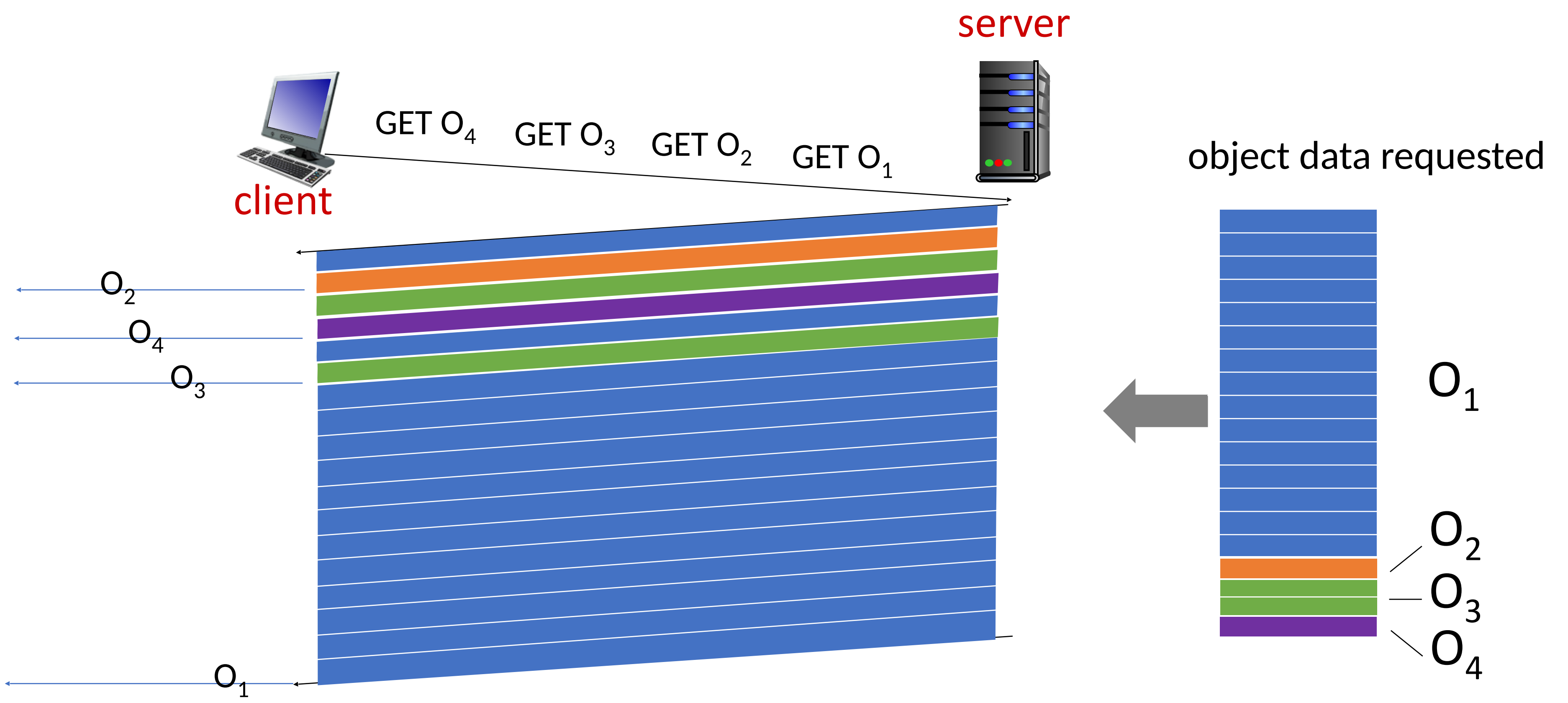

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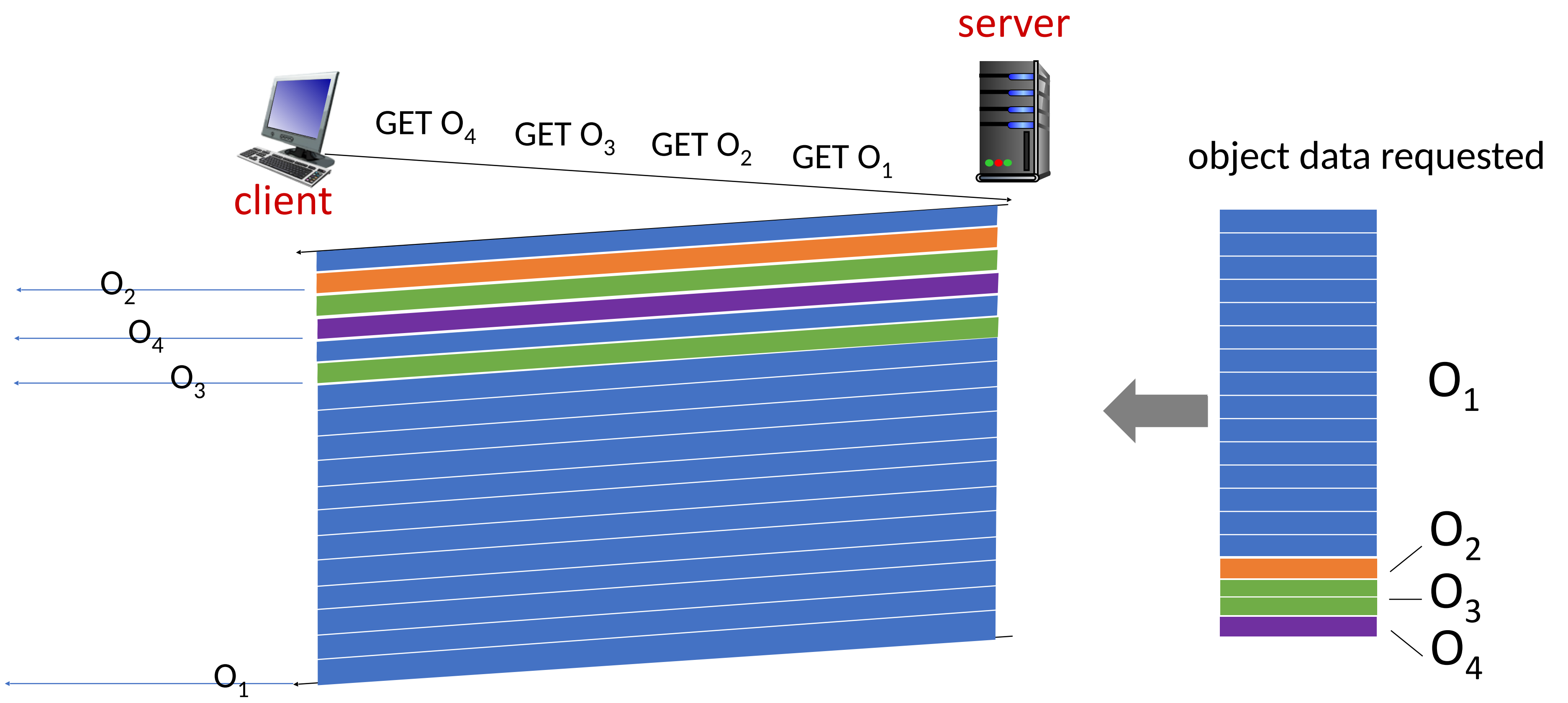

O_2, O_3, O_4 delivered quickly, O_1 slightly delayed

HTTP/2 to HTTP/3

HTTP/2 to HTTP/3

HTTP/2 over single TCP connection means:

- recovery from packet loss still stalls all object transmissions
  - as in HTTP 1.1, browsers have incentive to open multiple parallel TCP connections to reduce stalling, increase overall throughput
- no security over vanilla TCP connection
- HTTP/3: adds security, per object error- and congestion-control (more pipelining) over UDP
  - more on HTTP/3 in transport layer

Chapter 2: outline

- Principles of network applications
- Web and HTTP
- Electronic mail (E-mail)
  - SMTP, POP3, IMAP
- The Domain Name System (DNS)
- P2P applications
- video streaming and content distribution networks

E-mail

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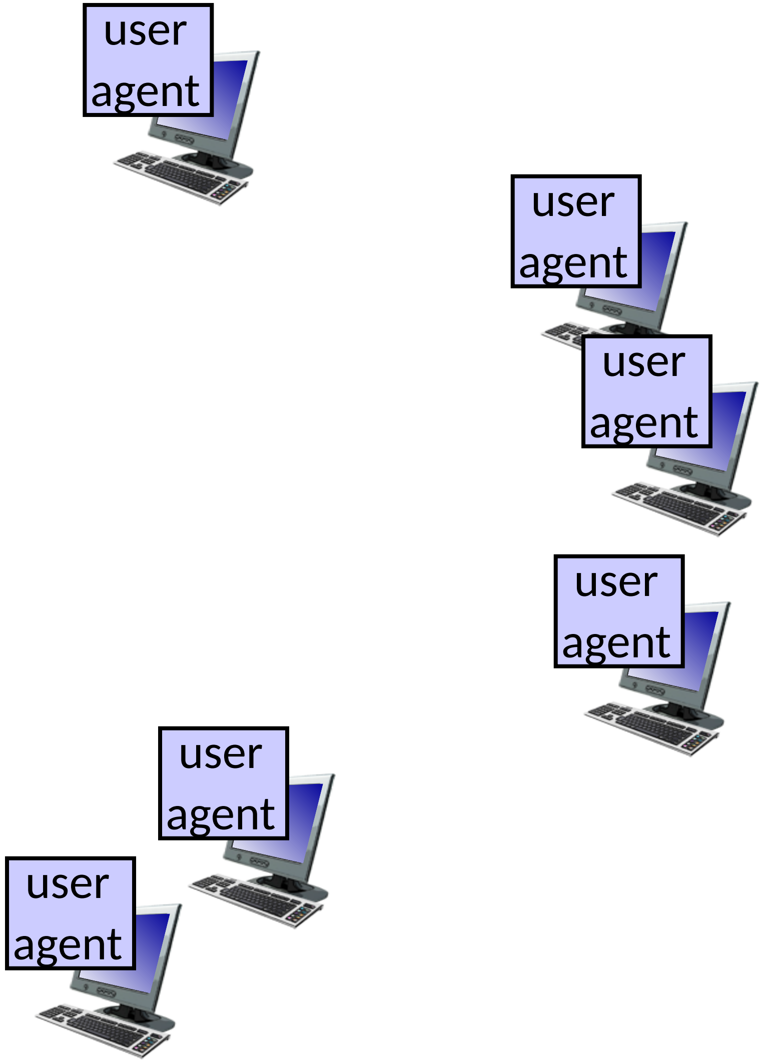

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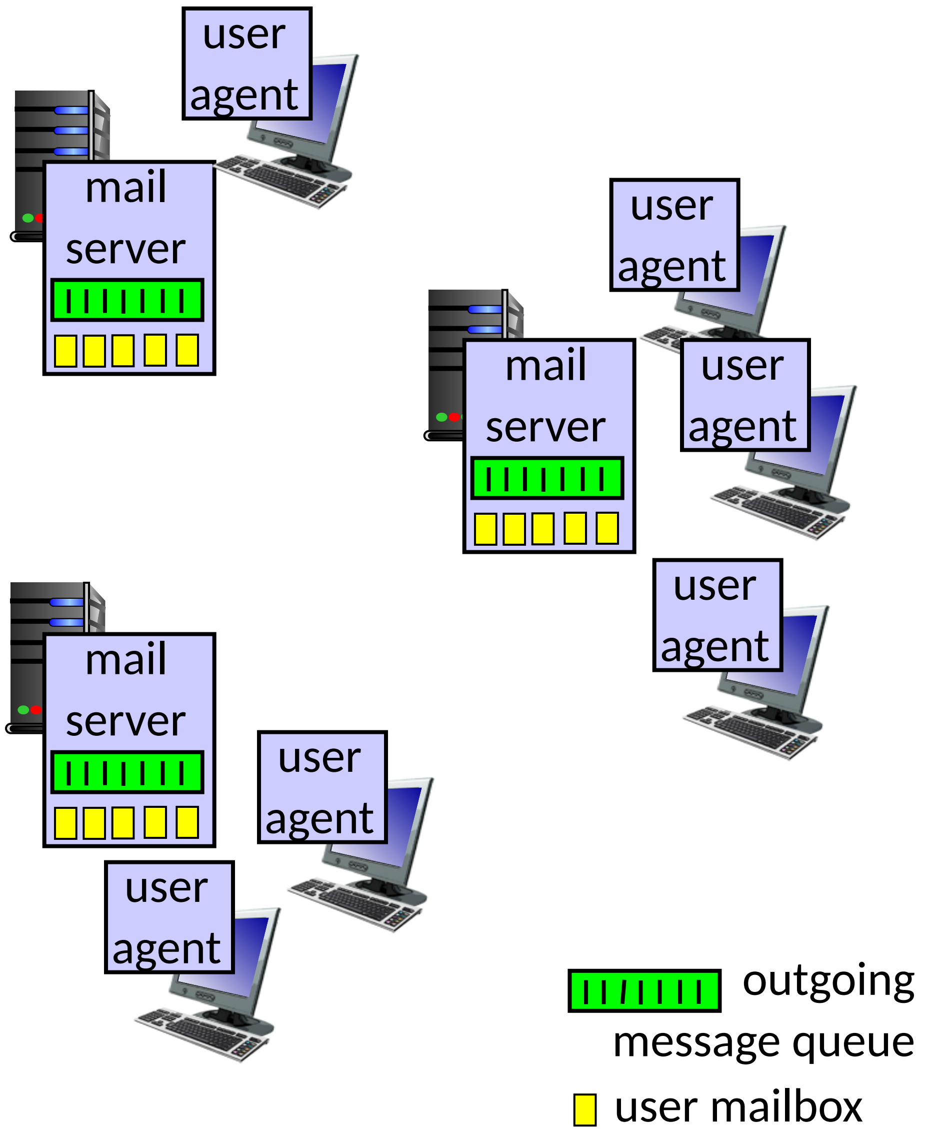

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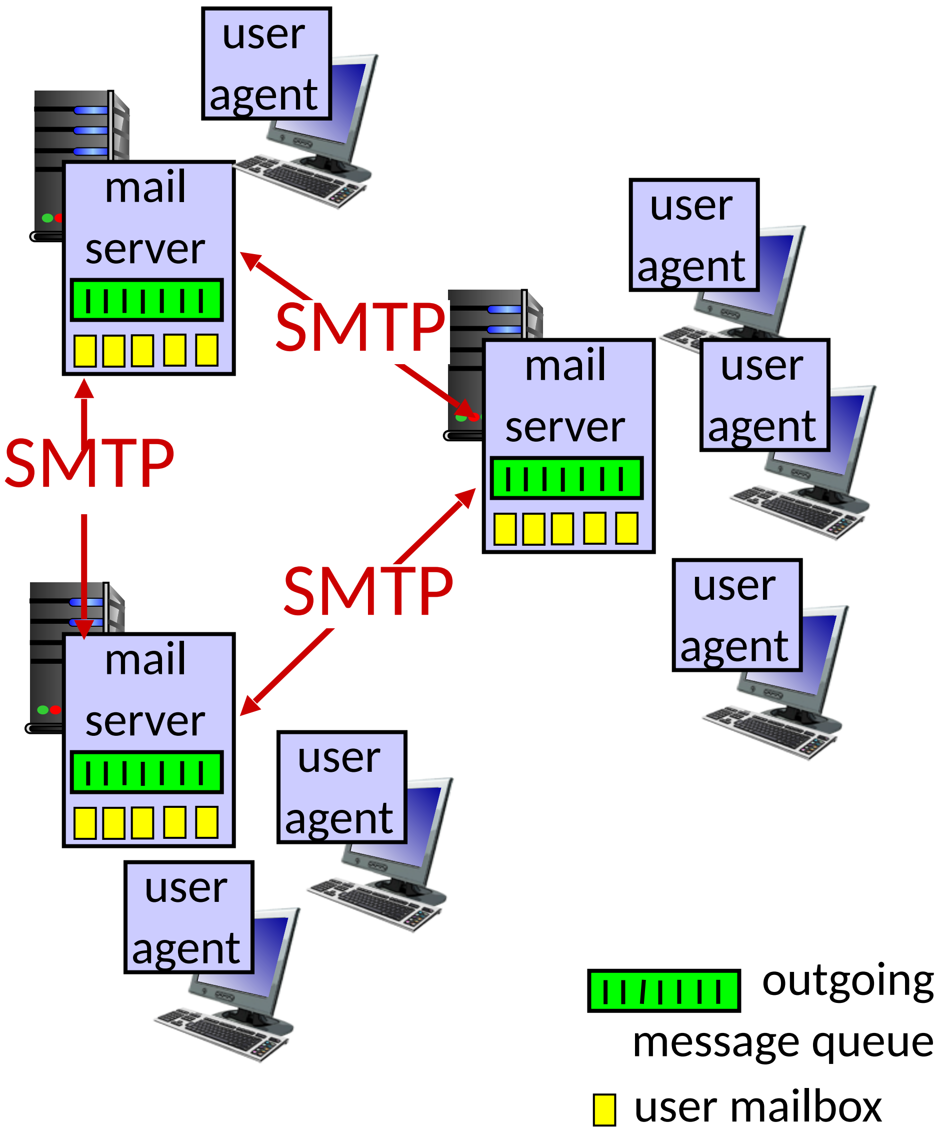
- simple mail transfer protocol: SMTP



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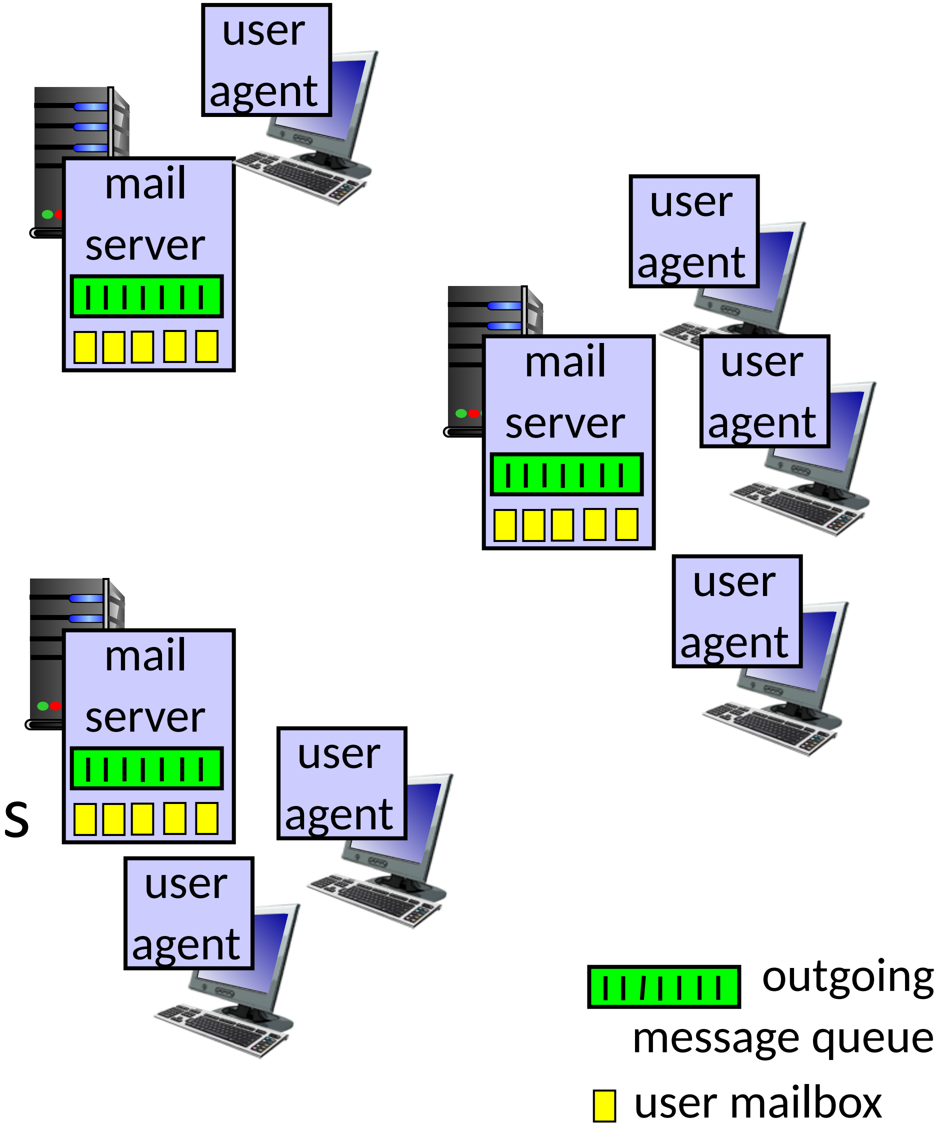
User Agent

- a.k.a. "mail reader"
- composing, editing, reading mail messages
- e.g., Outlook, iPhone mail client
- outgoing, incoming messages stored on server



E-mail: mail servers

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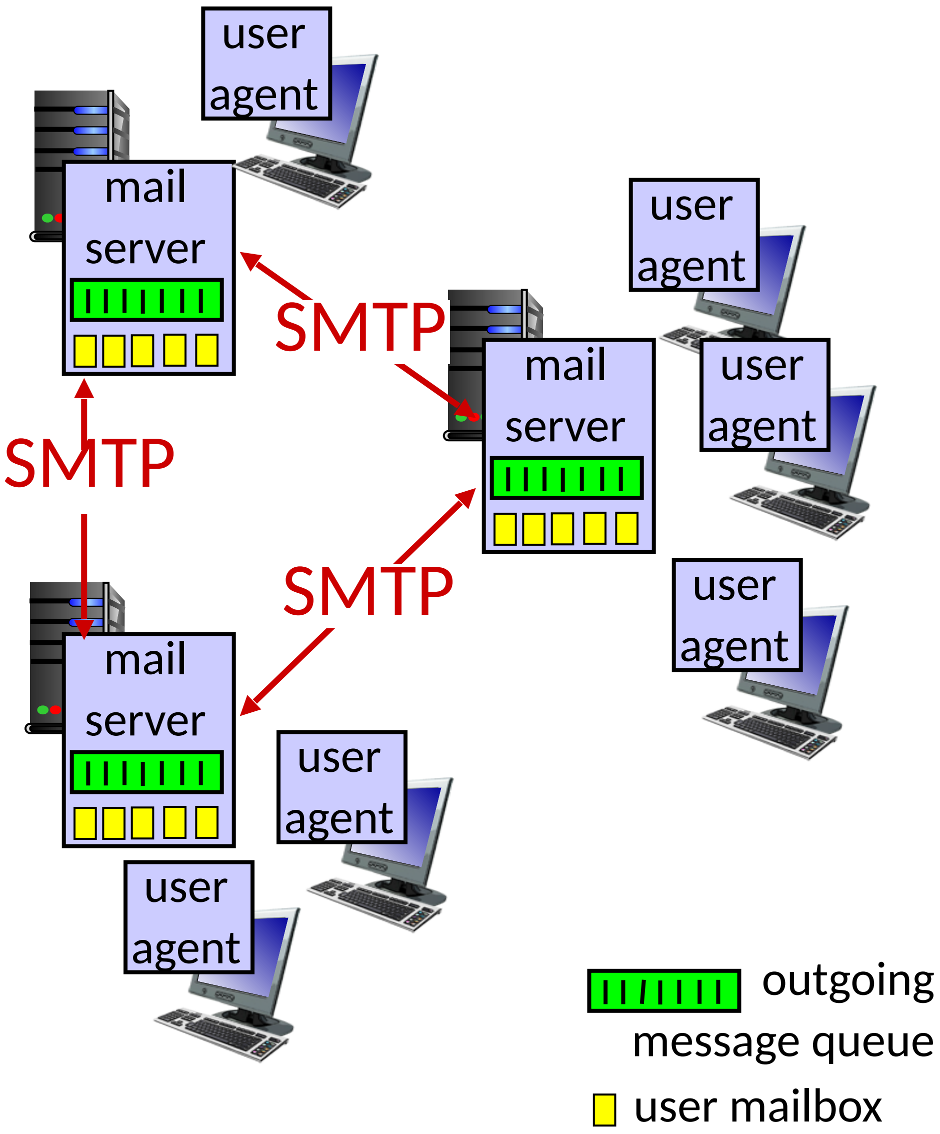
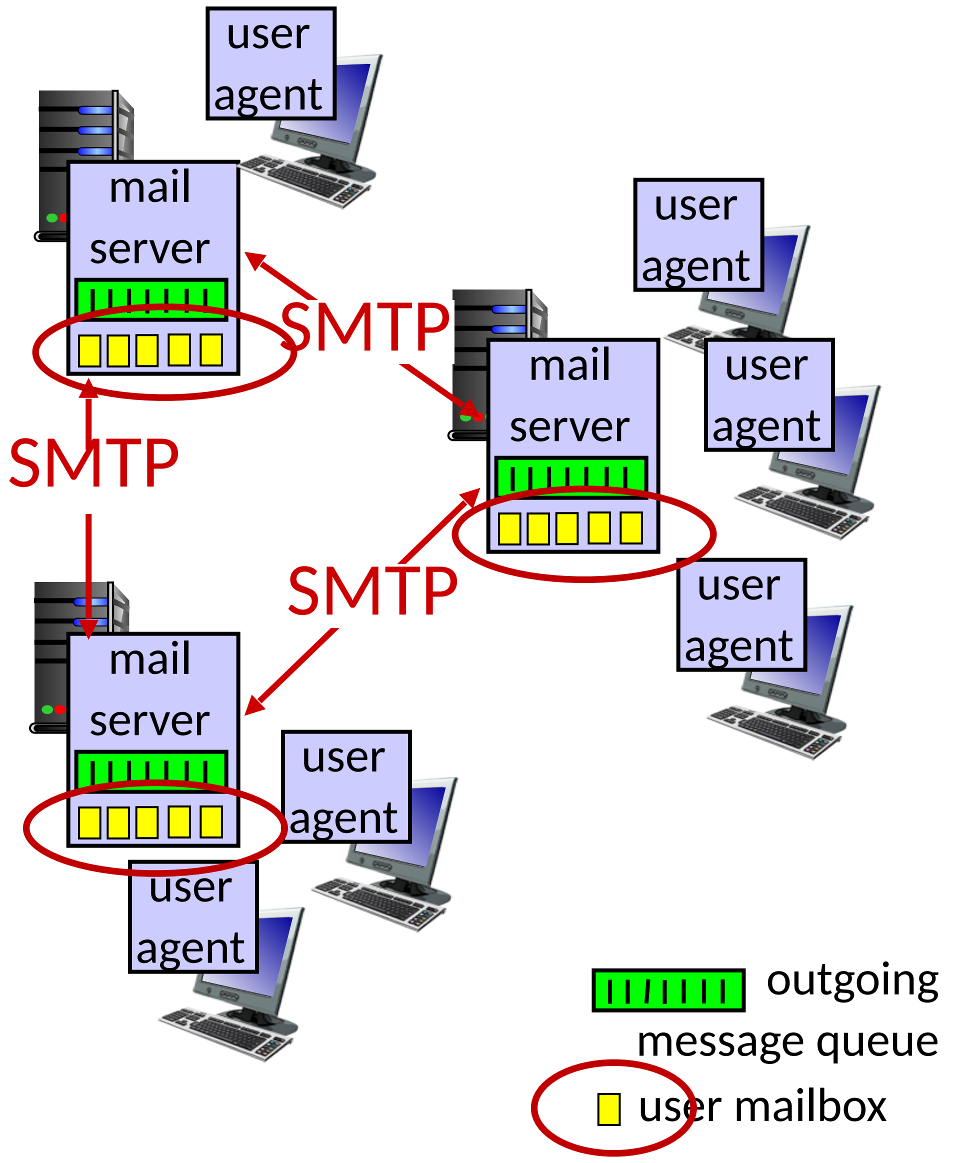


E-mail: mail servers

mail servers:

- *mailbox* contains incoming messages for user



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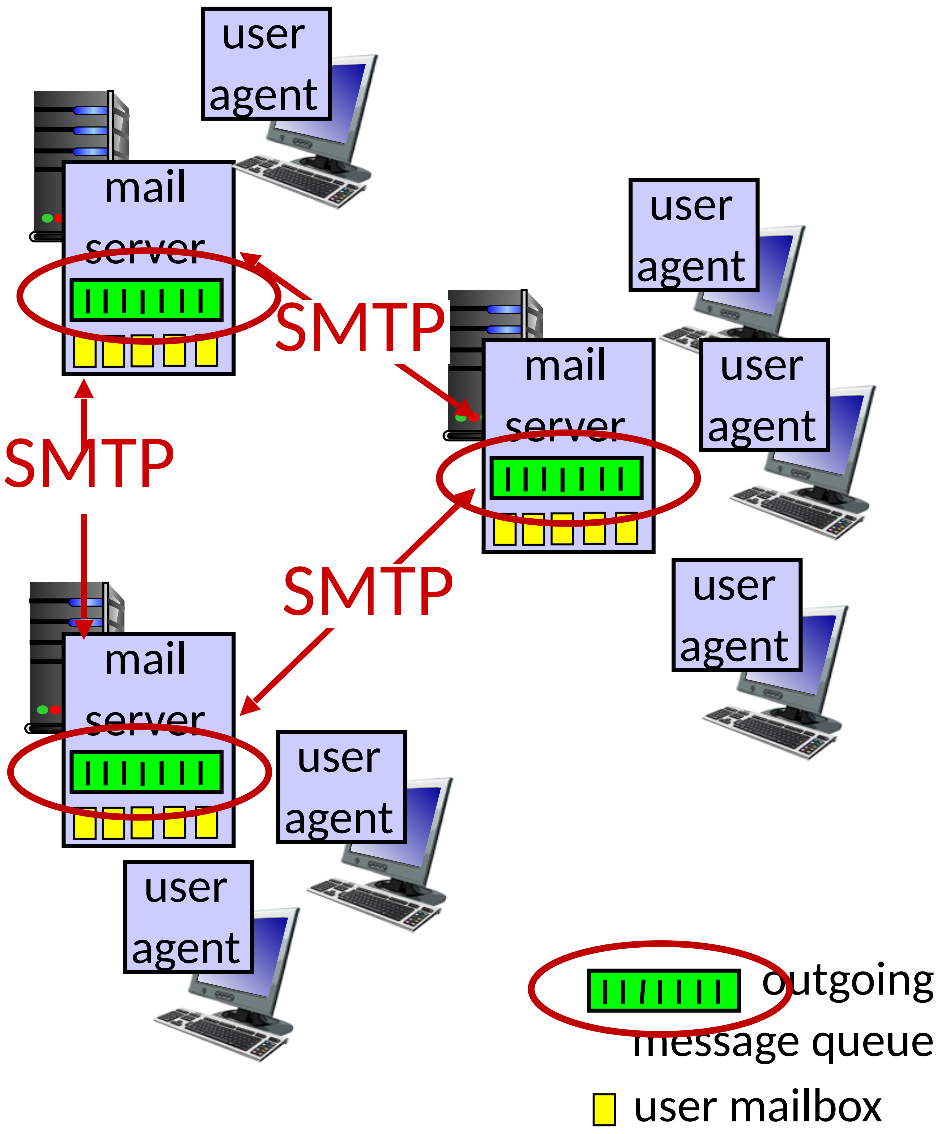

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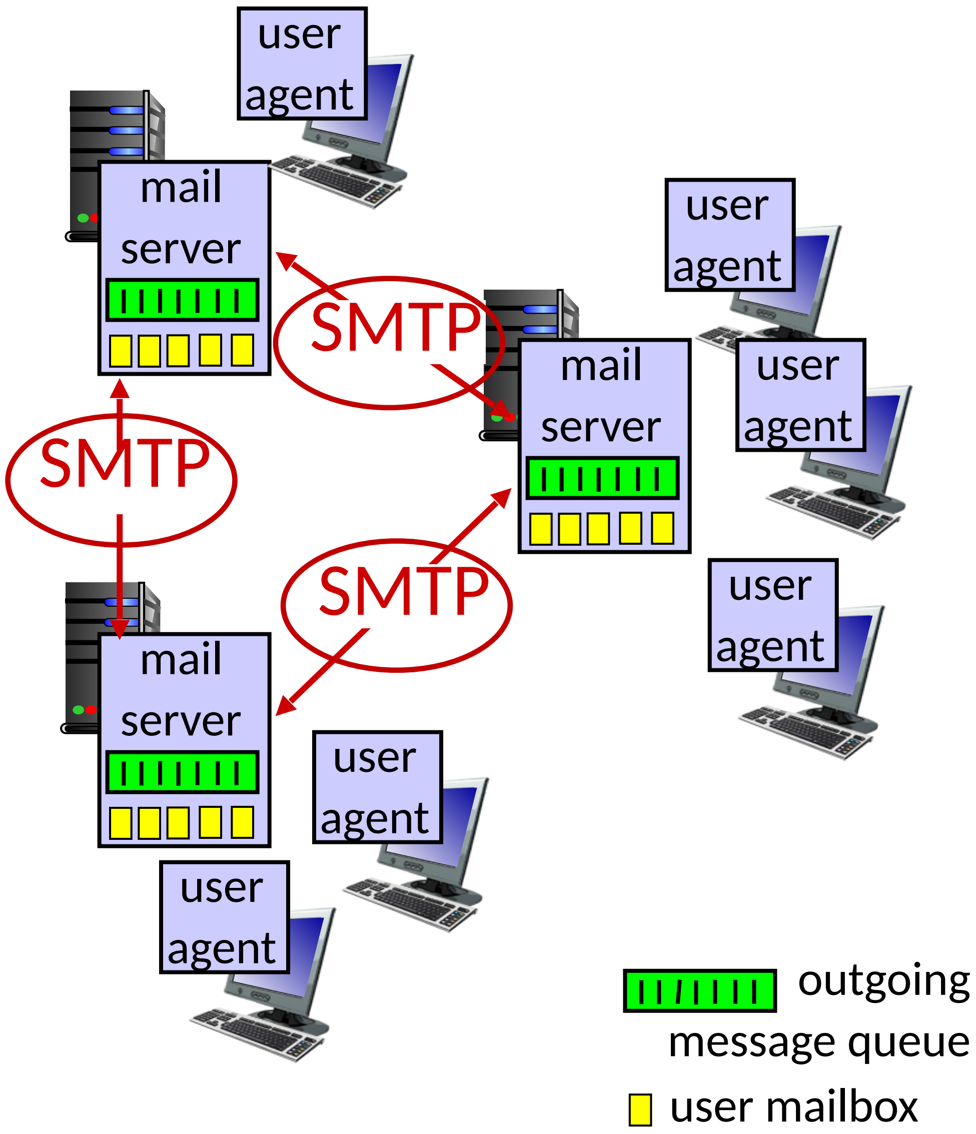
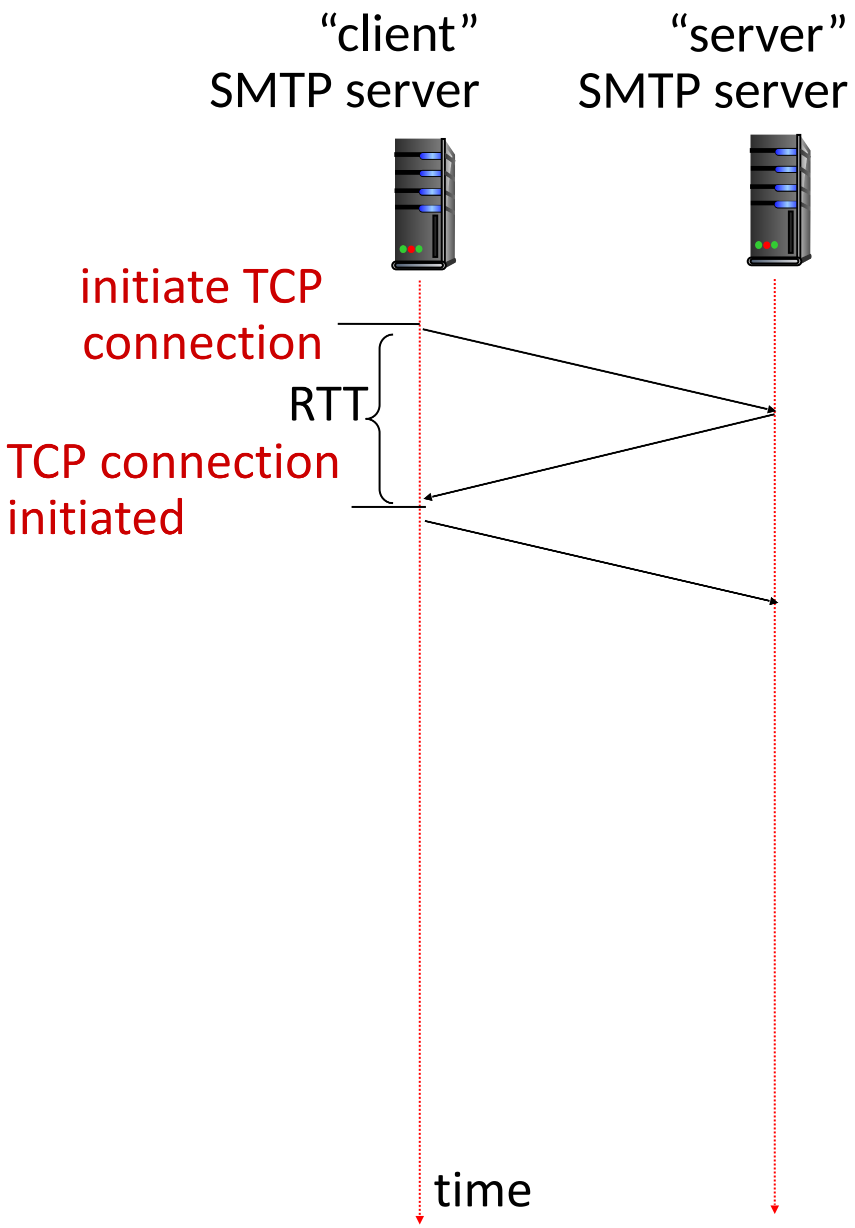
SMTP protocol between mail servers to send email messages

- client: sending mail server
- "server": receiving mail server



SMTP RFC (5321)

- uses TCP to reliably transfer email message from client (mail server initiating connection) to server, port 25
  - direct transfer: sending server (acting like client) to receiving server



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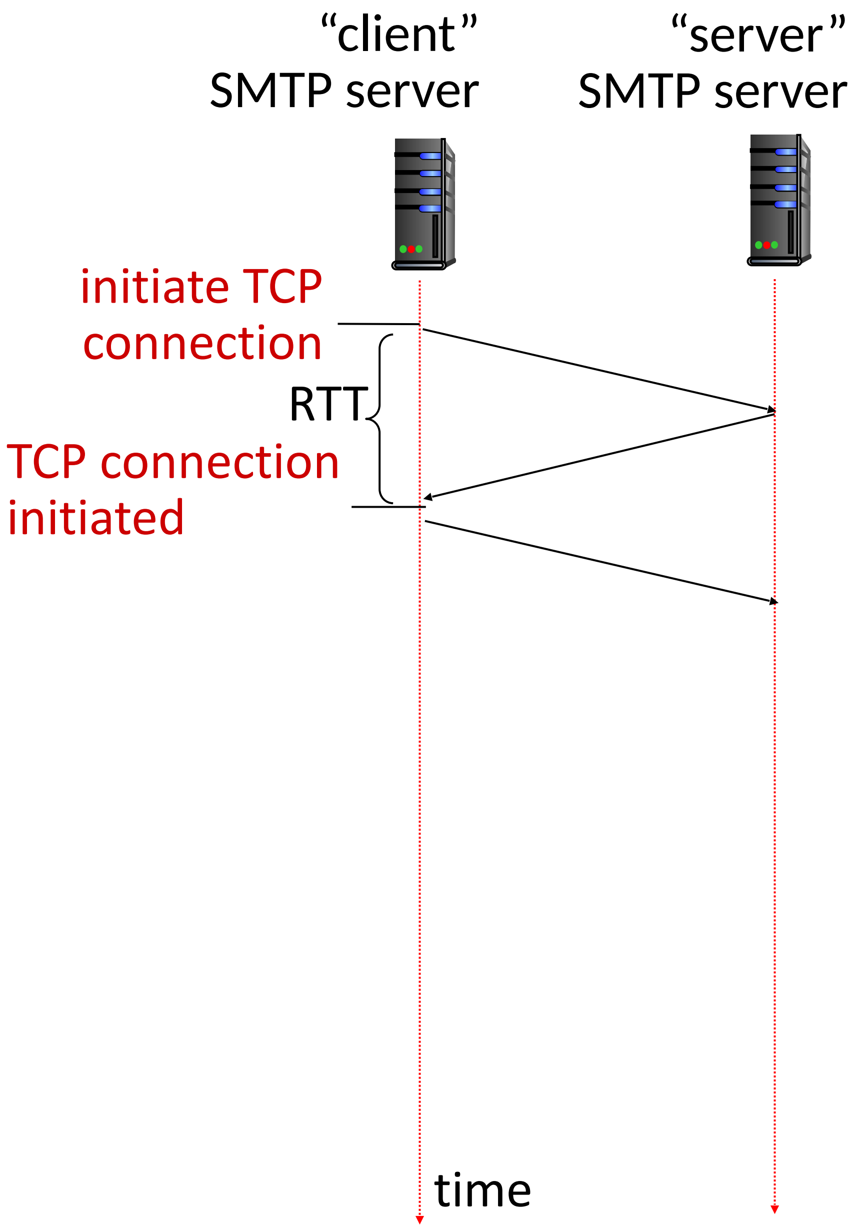

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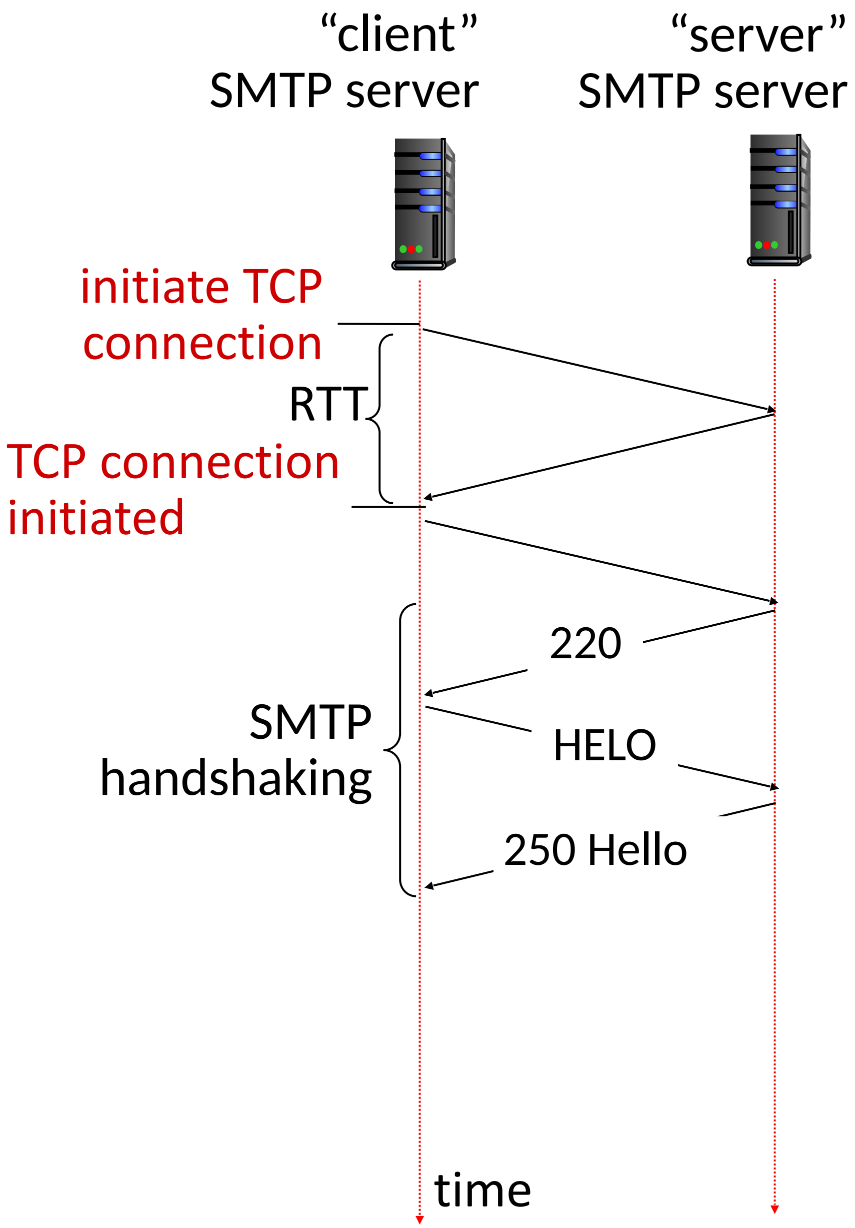

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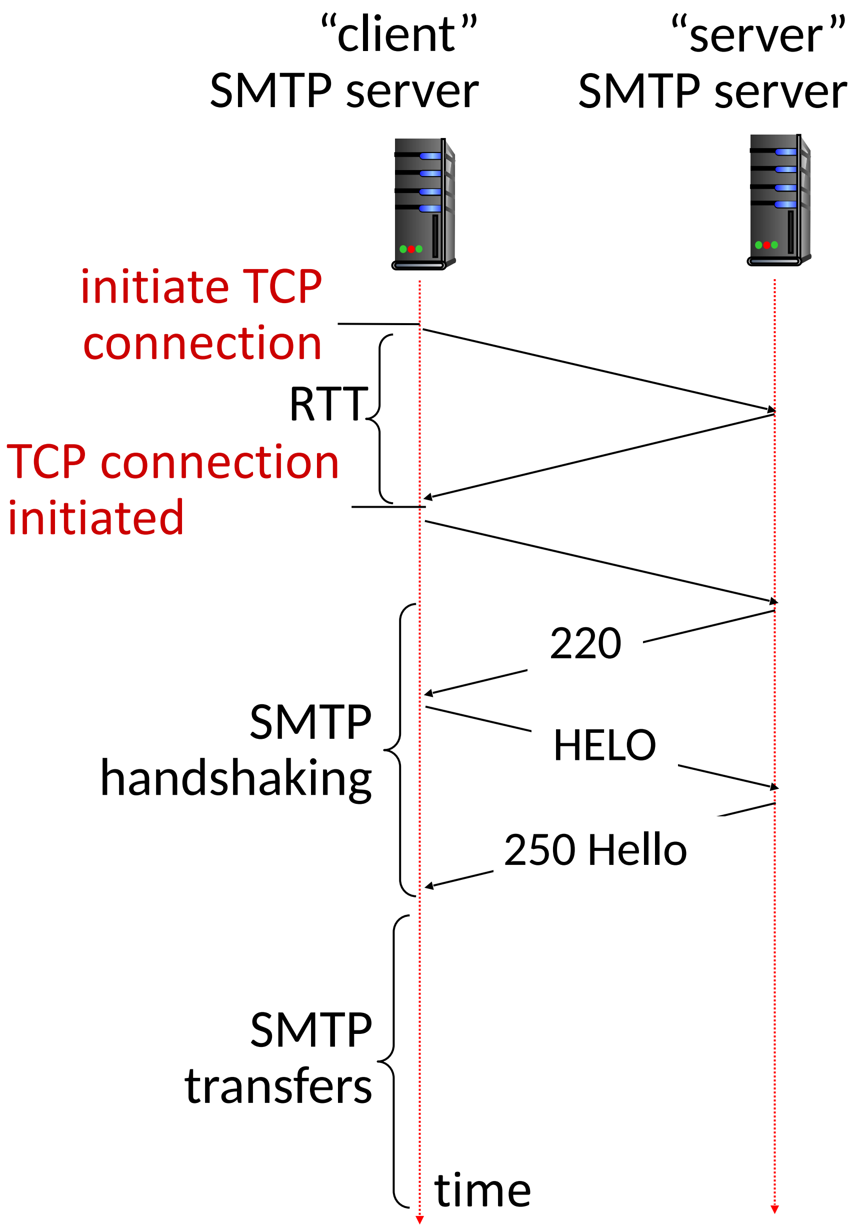

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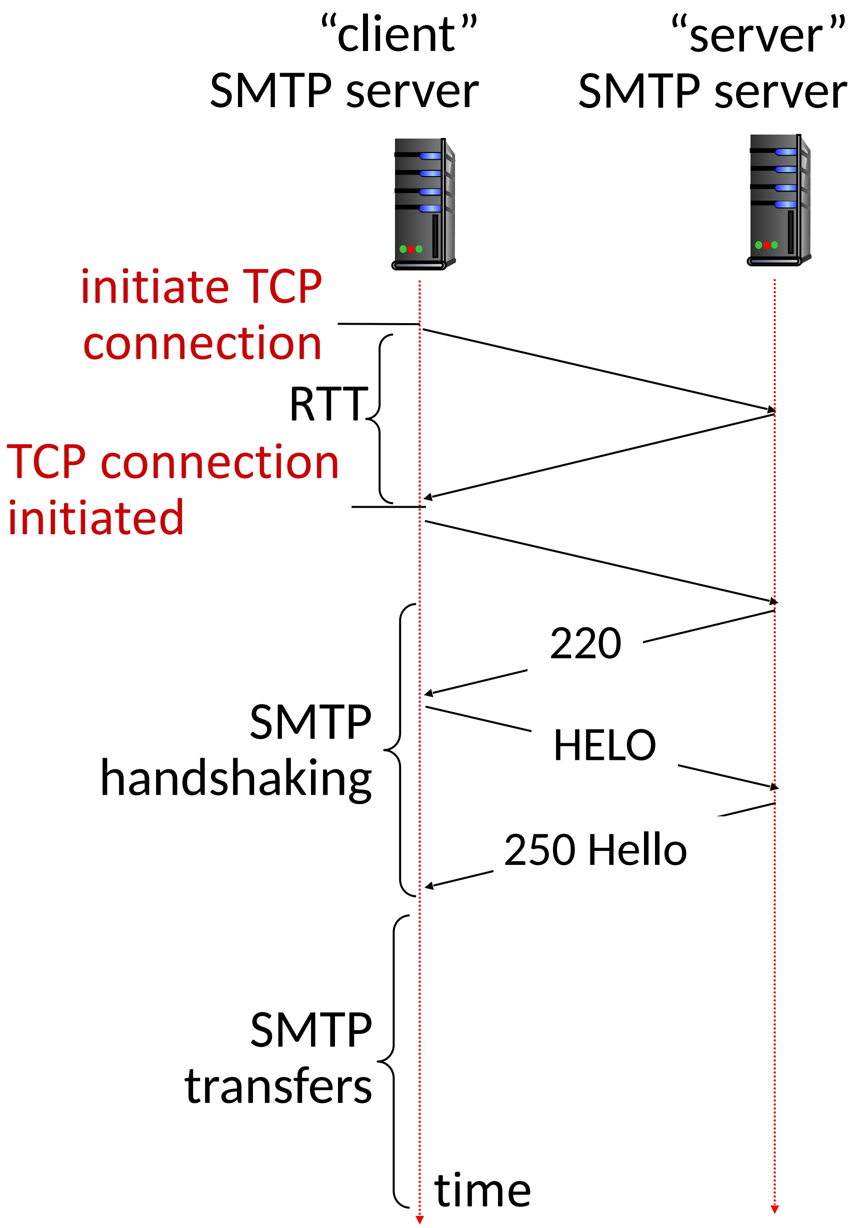
  - SMTP closure



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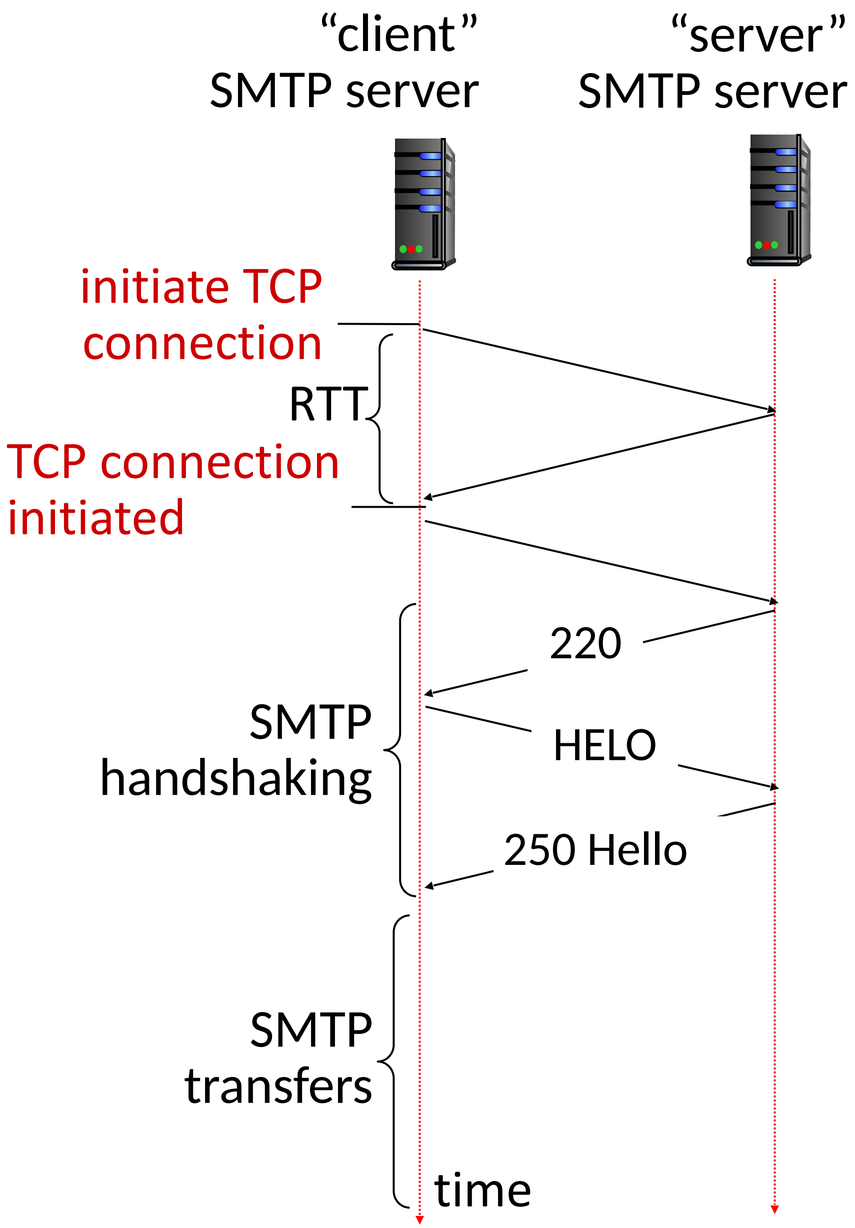
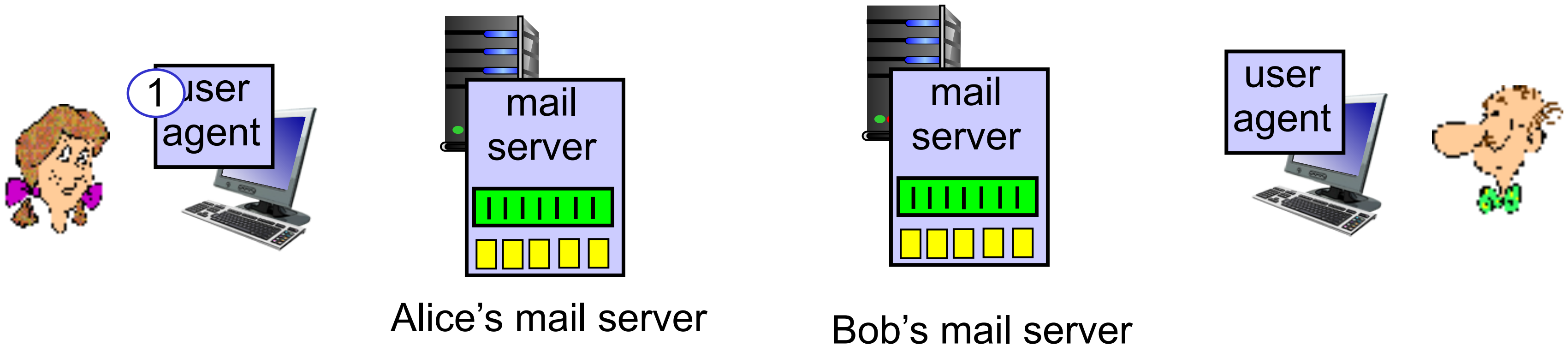
- three phases of transfer
  - SMTP handshaking (greeting)
  - SMTP transfer of messages
  - SMTP closure
- command/response interaction (like HTTP)
  - commands: ASCII text
  - response: status code and phrase



Scenario: Alice sends e-mail to Bob

1) Alice uses UA to compose e-mail message “to” bob@someschool.edu



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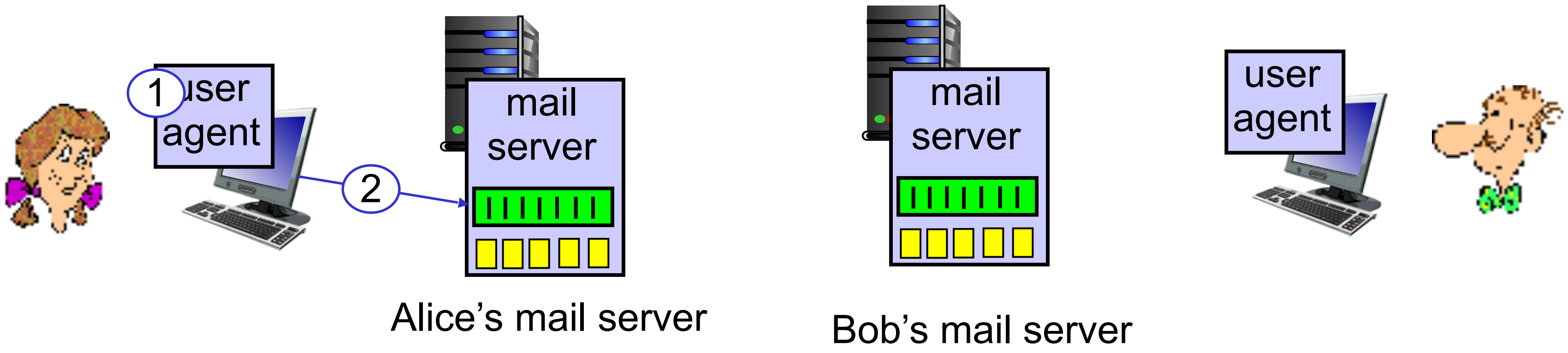
1) Alice uses UA to compose e-mail message “to” bob@someschool.edu

2) Alice’s UA sends message to her mail server using SMTP; message placed in message queue



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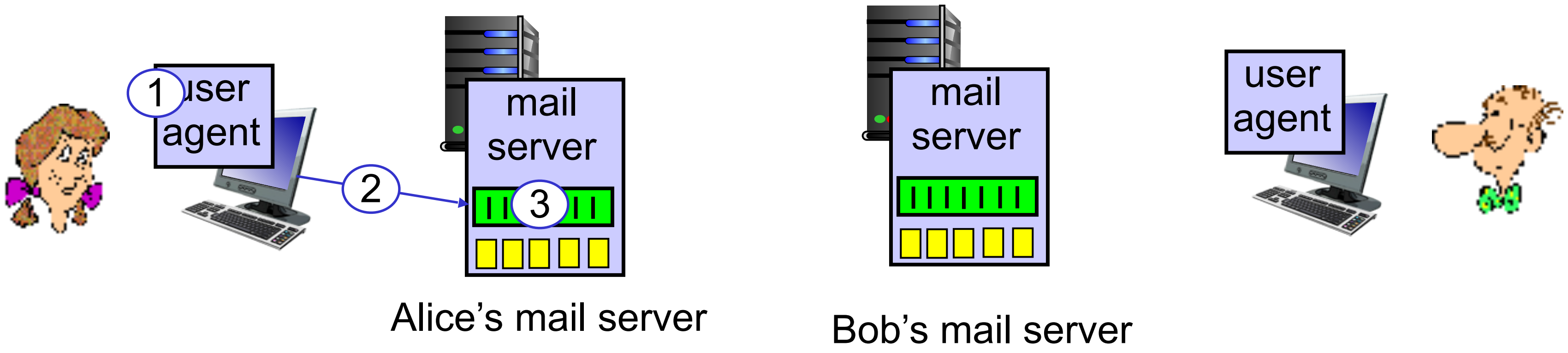
3) client side of SMTP at mail server opens TCP connection with Bob’s mail server



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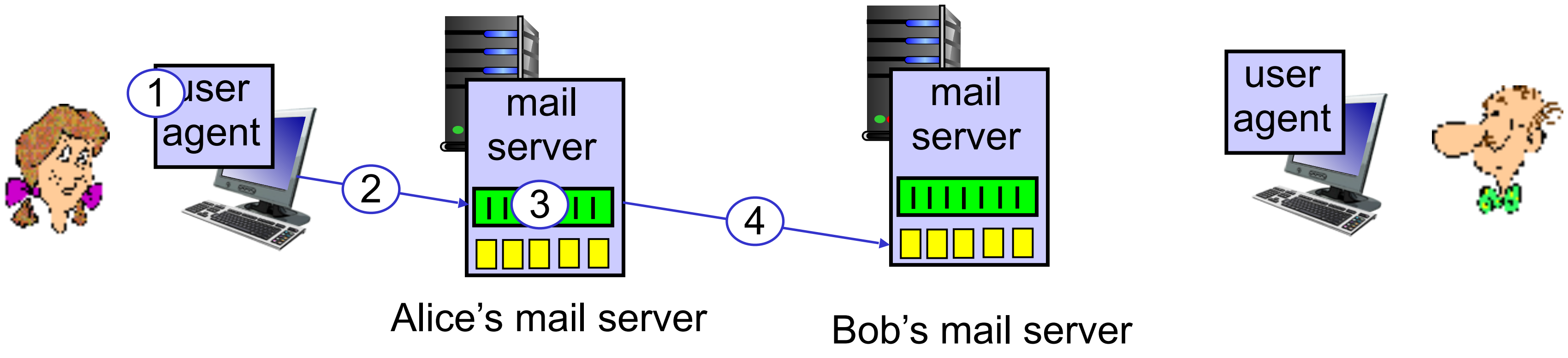

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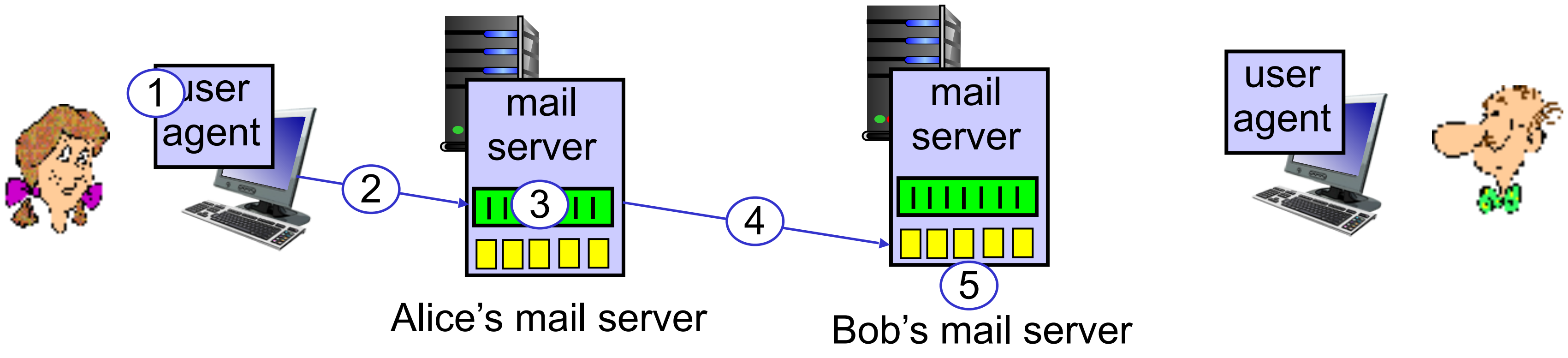

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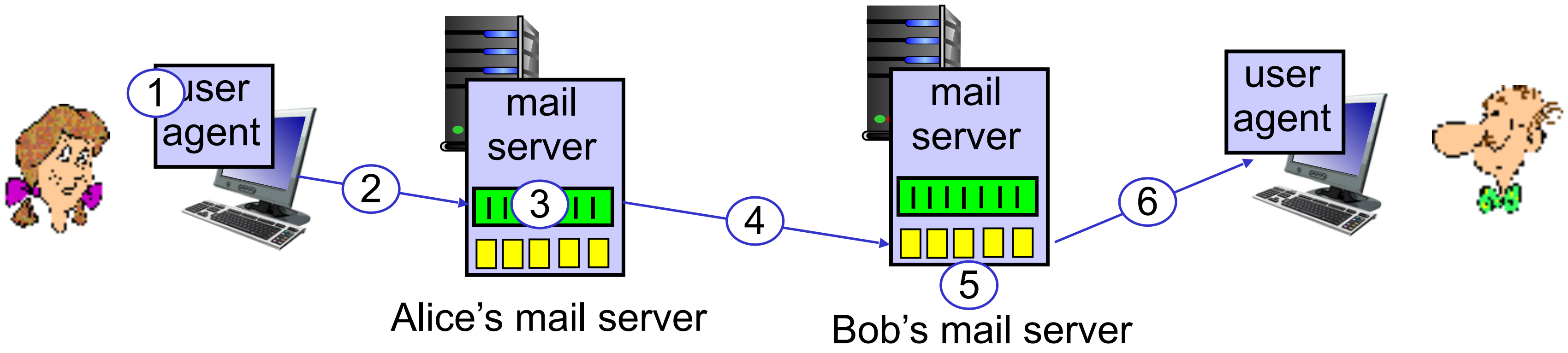

Sample SMTP interaction

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S: 220 hamburger.edu
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S: 250  Hello crepes.fr, pleased to meet you
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S: 250 alice@crepes.fr... Sender ok
C: RCPT TO: <bob@hamburger.edu>
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C: DATA
```

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S: 354 Enter mail, end with "." on a line by itself
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C: DATA
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C: Do you like ketchup?
C: How about pickles?
C: .
S: 250 Message accepted for delivery
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C: DATA
S: 354 Enter mail, end with "." on a line by itself
C: Do you like ketchup?
C: How about pickles?
C: .
S: 250 Message accepted for delivery
C: QUIT
S: 221 hamburger.edu closing connection
```

SMTP: observations

comparison with HTTP:

- HTTP: client pull
- SMTP: client push

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- HTTP: each object encapsulated in its own response message
- SMTP: multiple objects sent in multipart message

- SMTP uses persistent connections
- SMTP requires message (header & body) to be in 7-bit ASCII
- SMTP server uses CRLF.CRLF to determine end of message

Try SMTP interaction yourself

- **`telnet servername 25`**
- see 220 reply from server
- enter HELO, MAIL FROM, RCPT TO, DATA, QUIT commands

above lets you send email without using email client (reader)

Mail message format

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RFC 2822 defines *syntax* for e-mail message itself (like HTML defines syntax for web documents)

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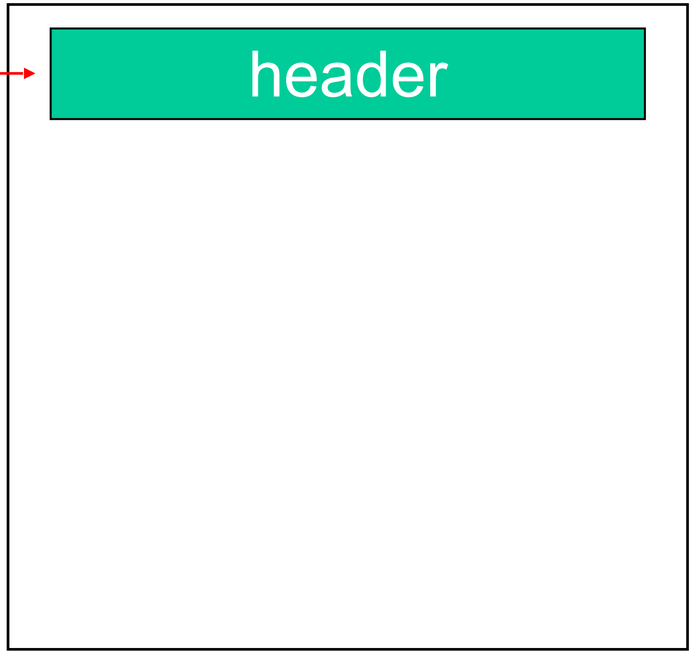

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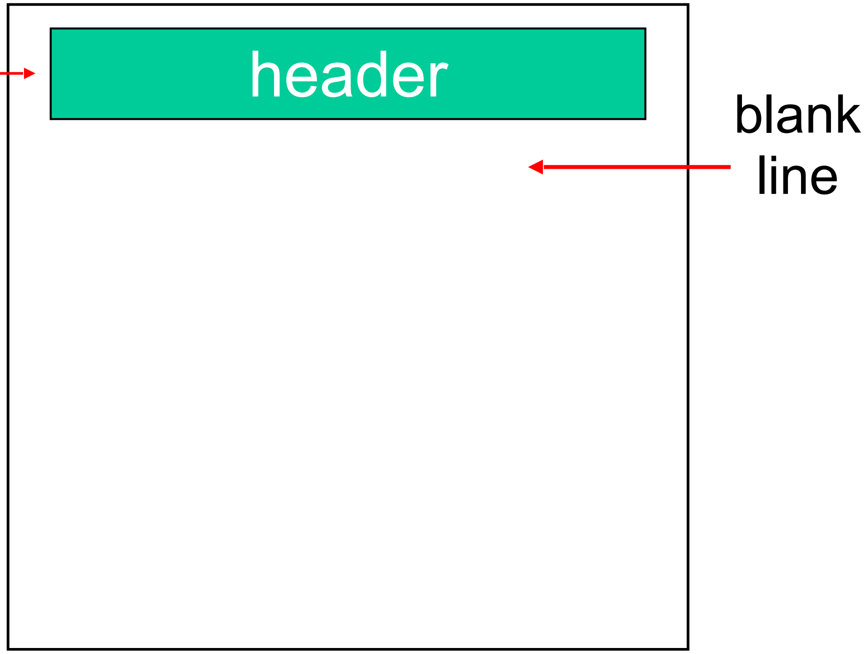

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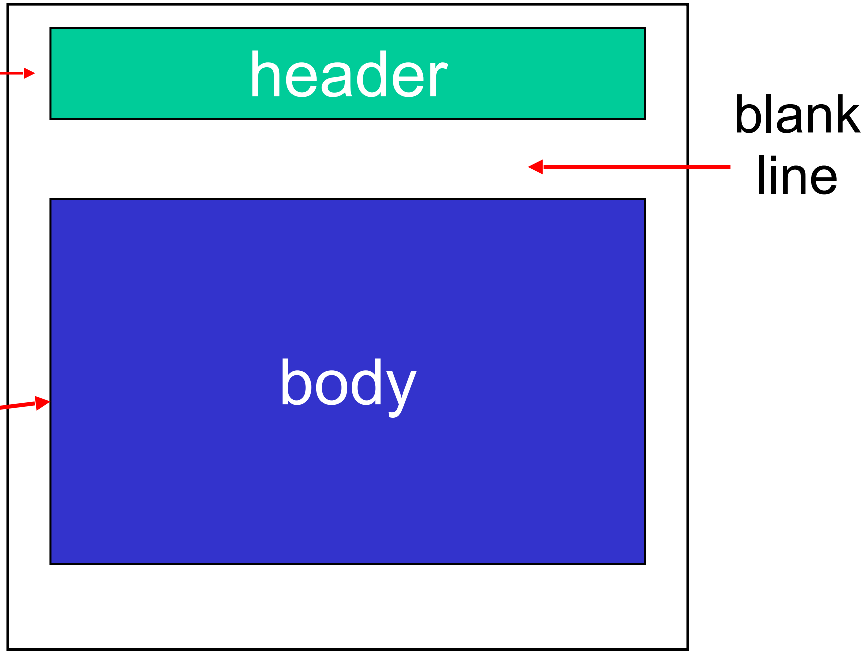
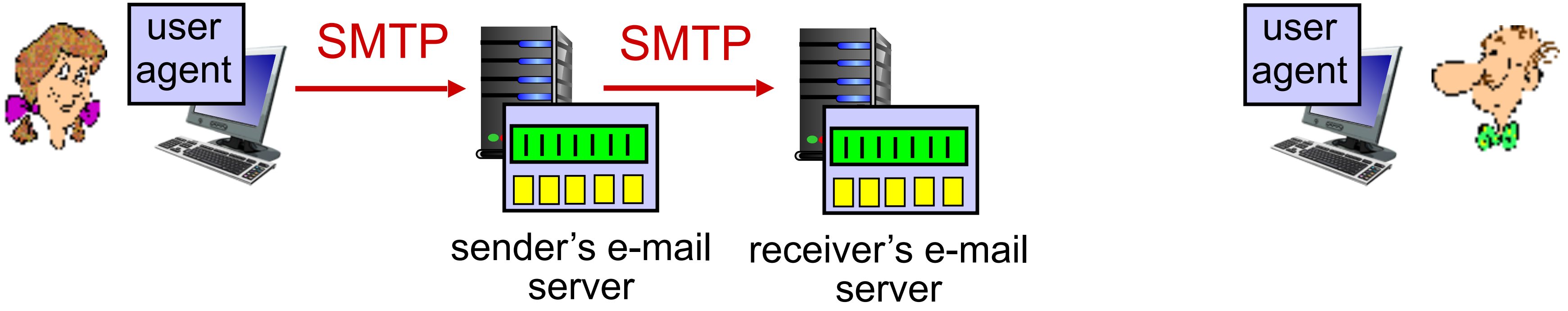
- Body: the "message" , ASCII characters only



Retrieving email: mail access protocols



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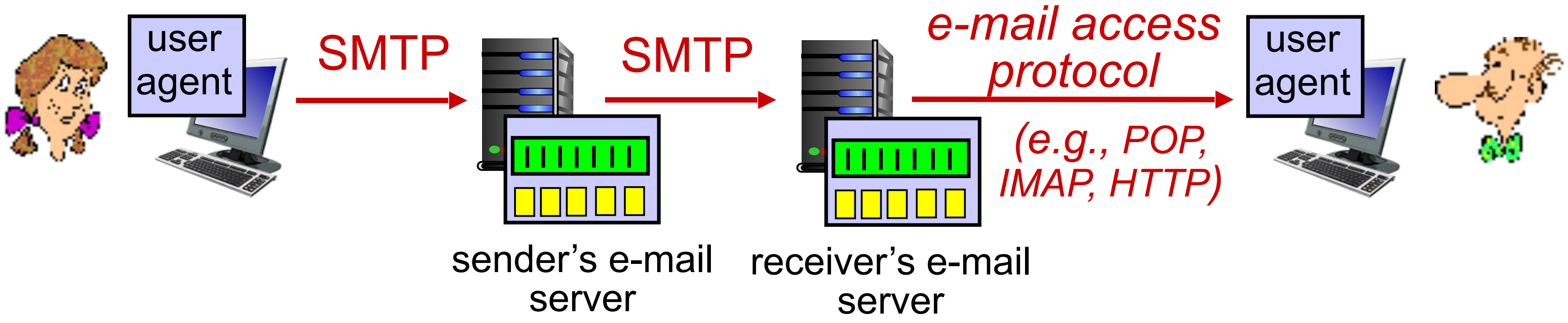

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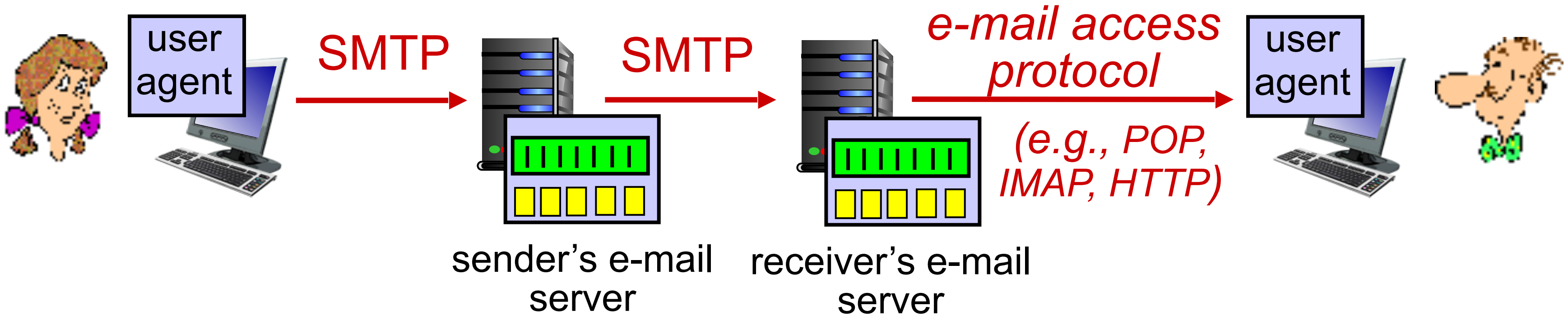

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- HTTP: gmail, Hotmail, Yahoo!Mail, etc. provides web-based interface on top of STMP (to send), IMAP (or POP) to retrieve e-mail messages

POP3 protocol

authorization phase

- client commands:
  - **`user`**: declare username
  - **`pass`**: password
- server responses
  - **`+OK`**
  - **`-ERR`**

```
S: +OK POP3 server ready
C: user bob
S: +OK
C: pass hungry
S: +OK user successfully logged on
```

transaction phase, client:

- **`list`**: list message numbers
- **`retr`**: retrieve message by number
- **`dele`**: delete
- **`quit`**

```
C: list
S: 1 498
S: 2 912
S: .
C: retr 1
S: <message 1 contents>
S: .
C: dele 1
C: retr 2
S: <message 2 contents>
S: .
C: dele 2
C: quit
S: +OK POP3 server signing off
```

POP3 (more) and IMAP

more about POP3

- previous example uses POP3 “download and delete” mode
  - Bob cannot re-read e-mail if he changes client
- POP3 “download-and-keep”: copies of messages on different clients
- POP3 is stateless across sessions

IMAP

- keeps all messages in one place: at server
- allows user to organize messages in folders
- keeps user state across sessions:
  - names of folders and mappings between message IDs and folder name

Chapter 2: outline

- Principles of network applications
- Web and HTTP
- Electronic mail (E-mail)
  - SMTP, POP3, IMAP
- The Domain Name System (DNS)
- P2P applications
- Video streaming and content distribution networks

DNS: Domain Name System

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Domain Name System (DNS):

- *distributed database* implemented in hierarchy of many *name servers*
- *application-layer protocol:* hosts, DNS servers communicate to *resolve* names (address/name translation)
  - *note:* core Internet function, implemented as application-layer protocol
  - complexity at network's "edge"

DNS: services, structure

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- hostname-to-IP-address translation

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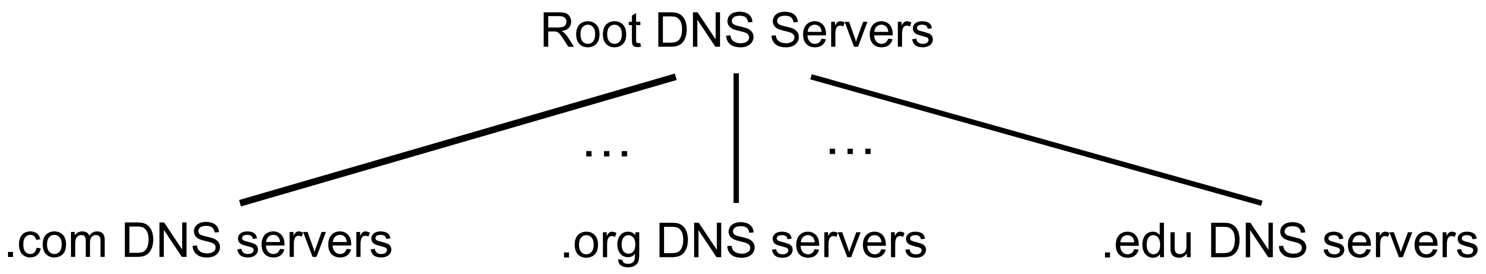
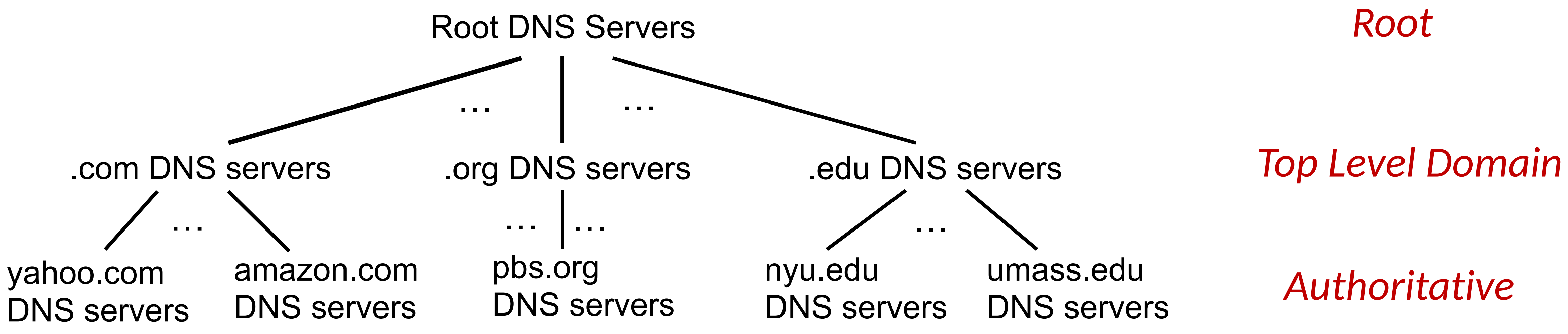


Root

Top Level Domain

DNS: a distributed, hierarchical database



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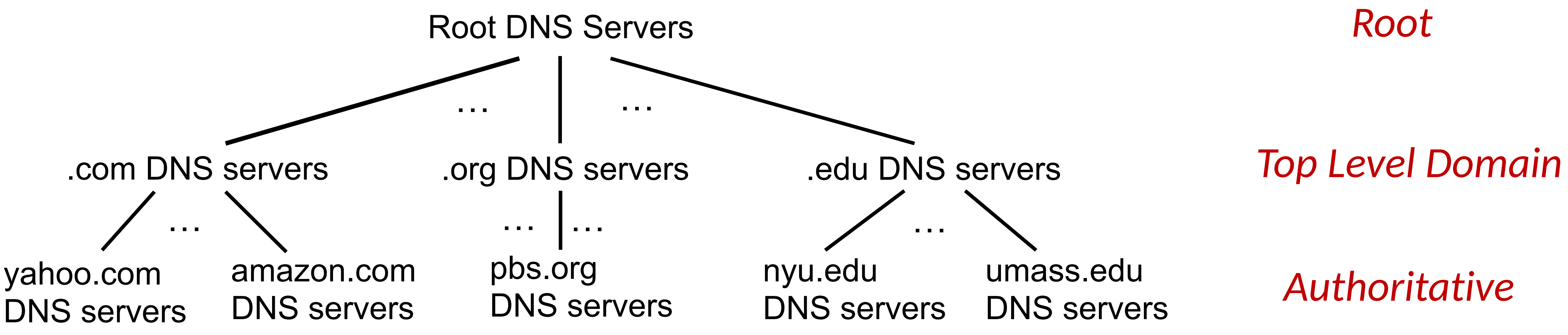

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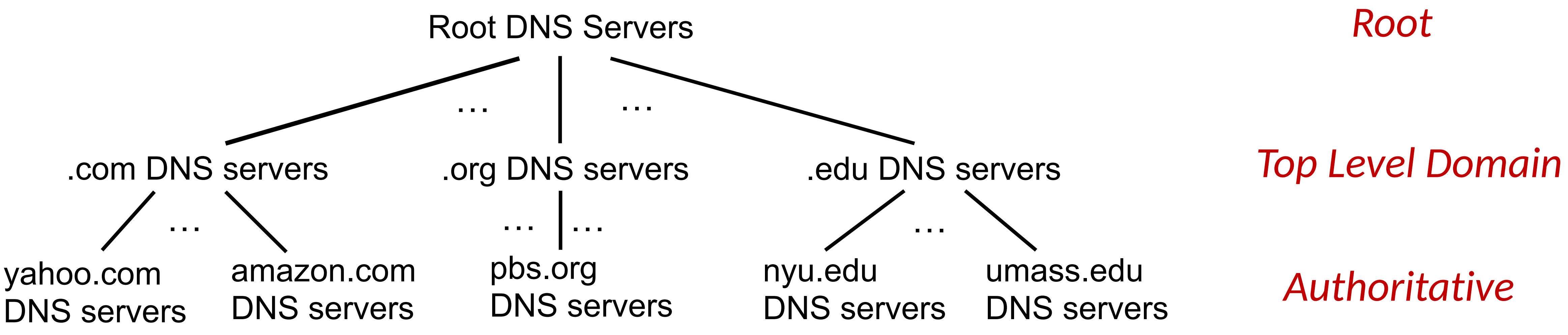

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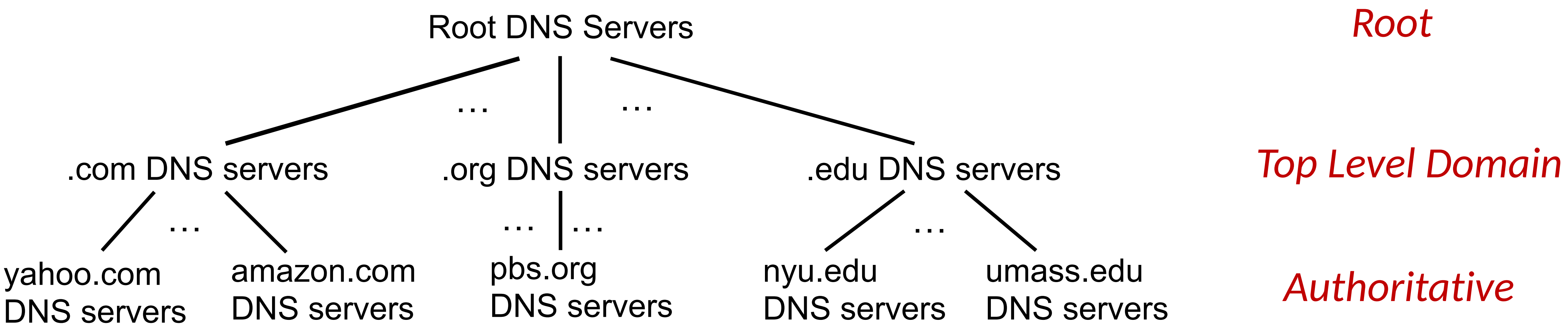

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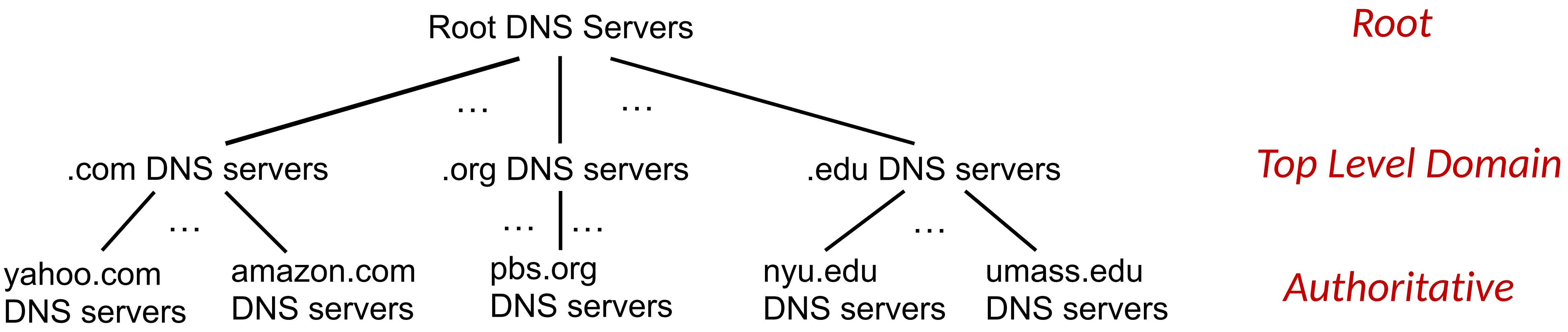

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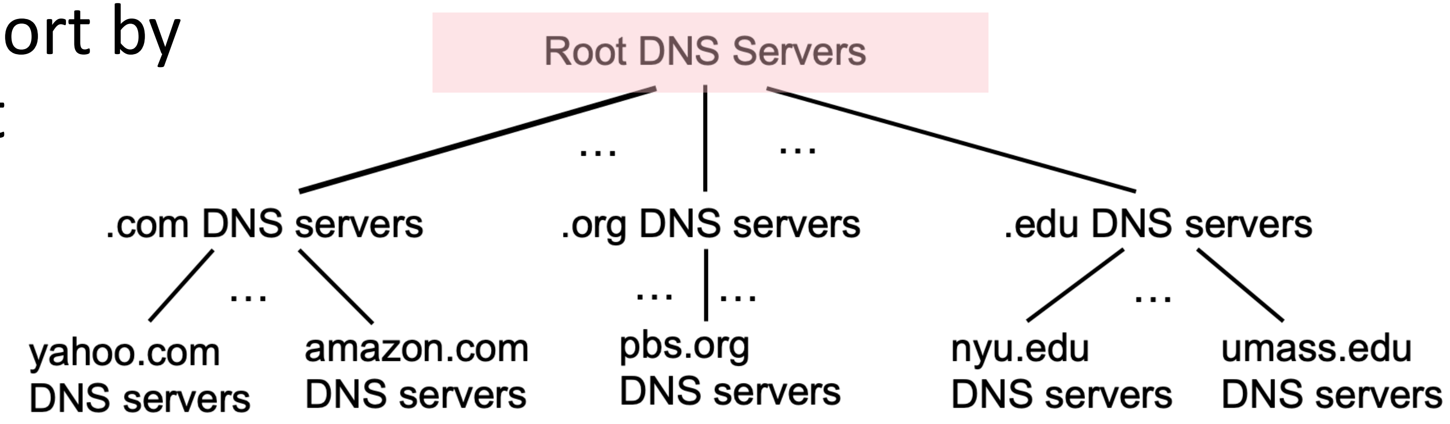

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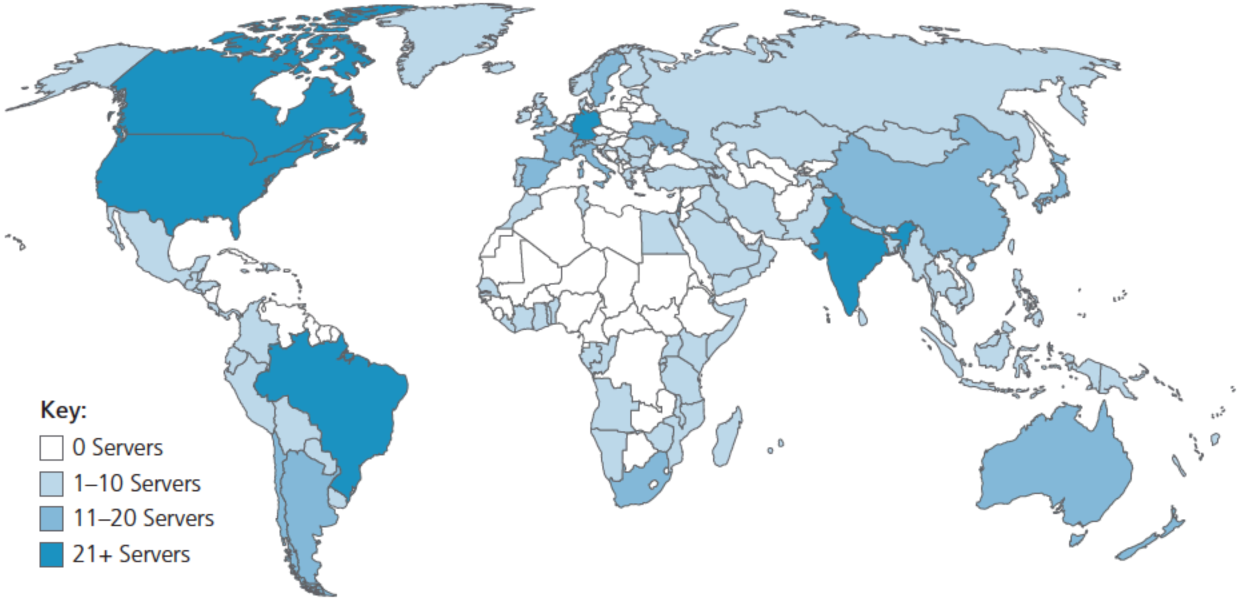
13 logical root name "servers" worldwide each "server" replicated many times (~200 servers in US)



Top-Level Domain, and authoritative servers

Top-Level Domain (TLD) servers:

- responsible for .com, .org, .net, .edu, .aero, .jobs, .museums, and all top-level country domains, e.g.: .cn, .uk, .fr, .ca, .jp
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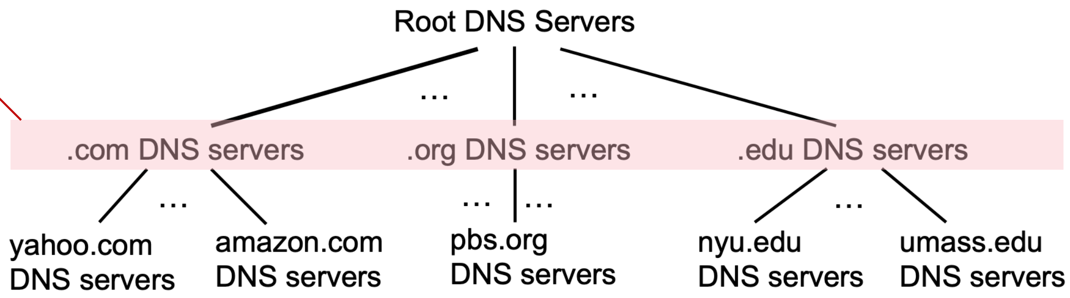

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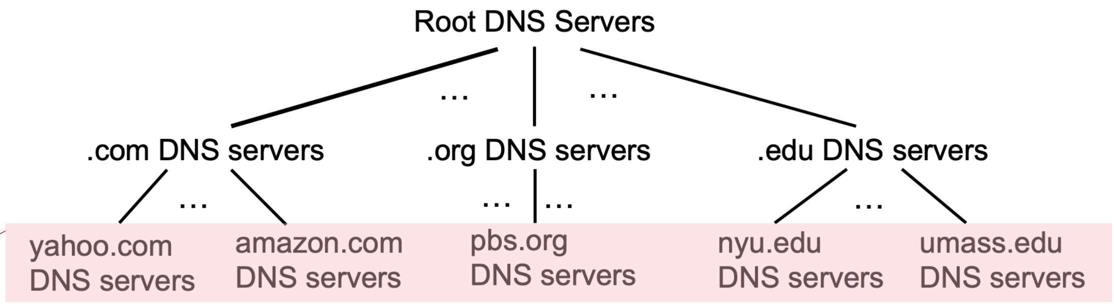

authoritative DNS servers:

- organization’s own DNS server(s), providing authoritative hostname to IP mappings for organization’s named hosts
- can be maintained by organization or service provider

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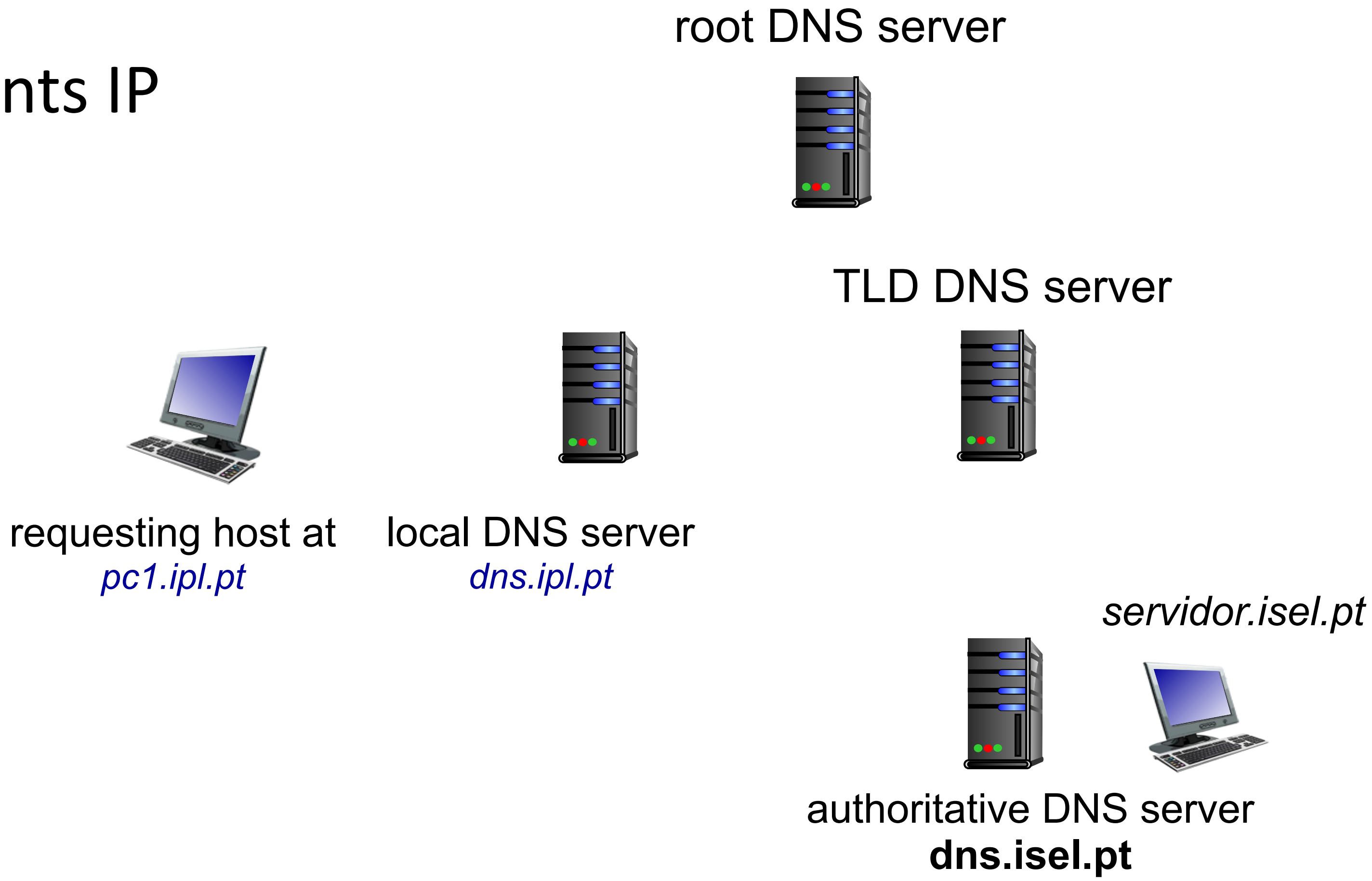
Example: host at pc1.ipl.pt wants IP address for servidor.isel.pt



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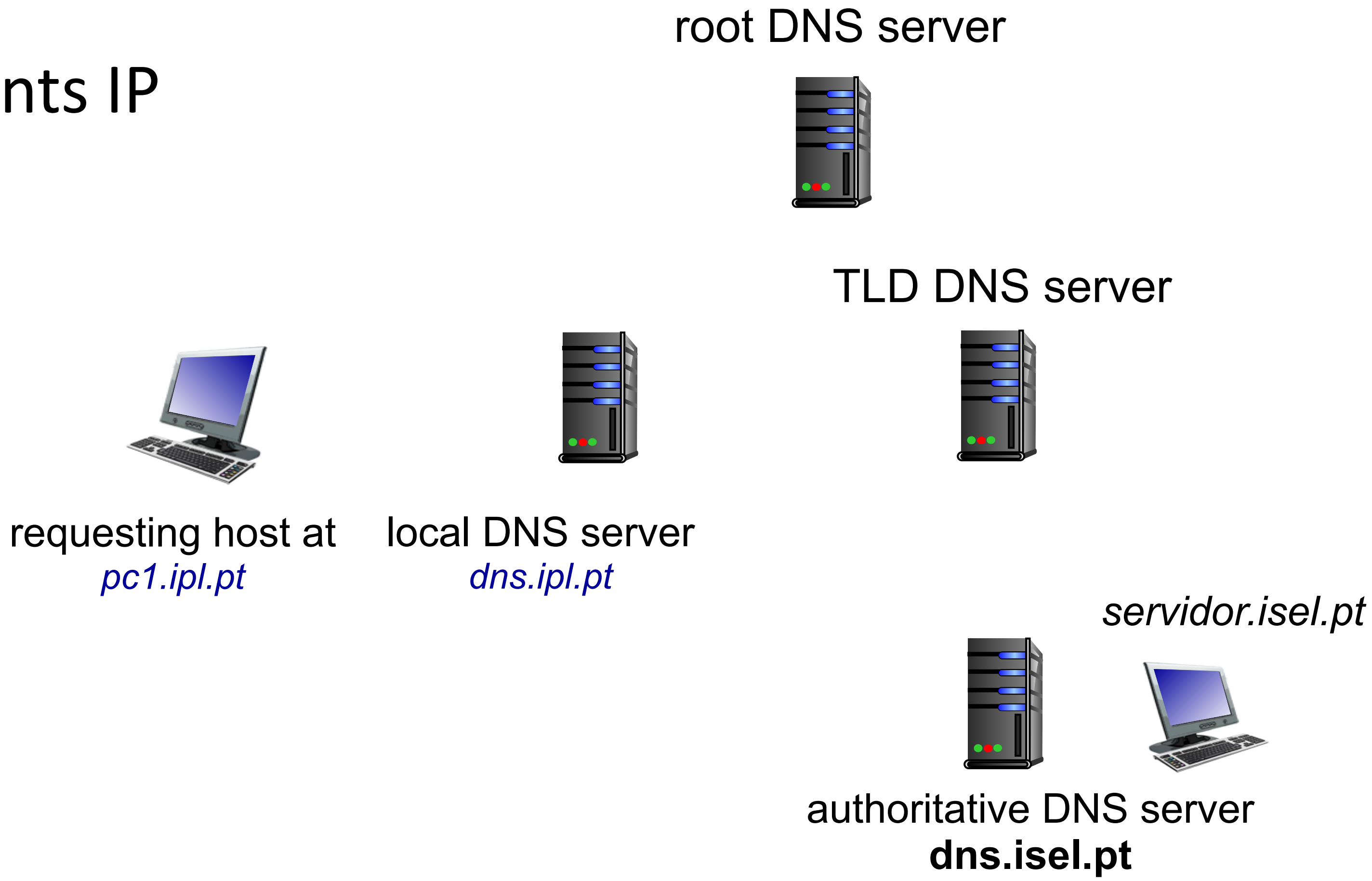

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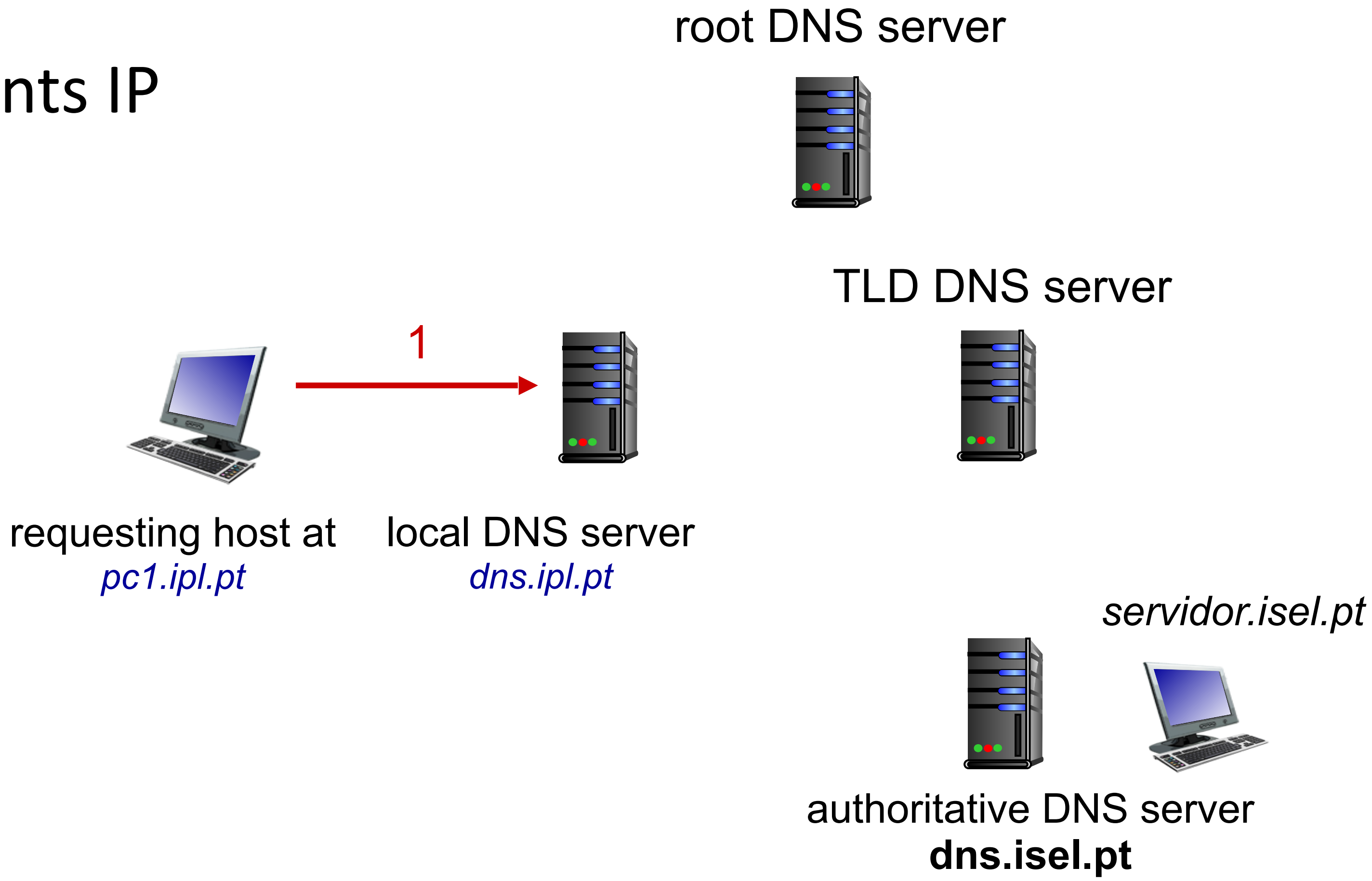

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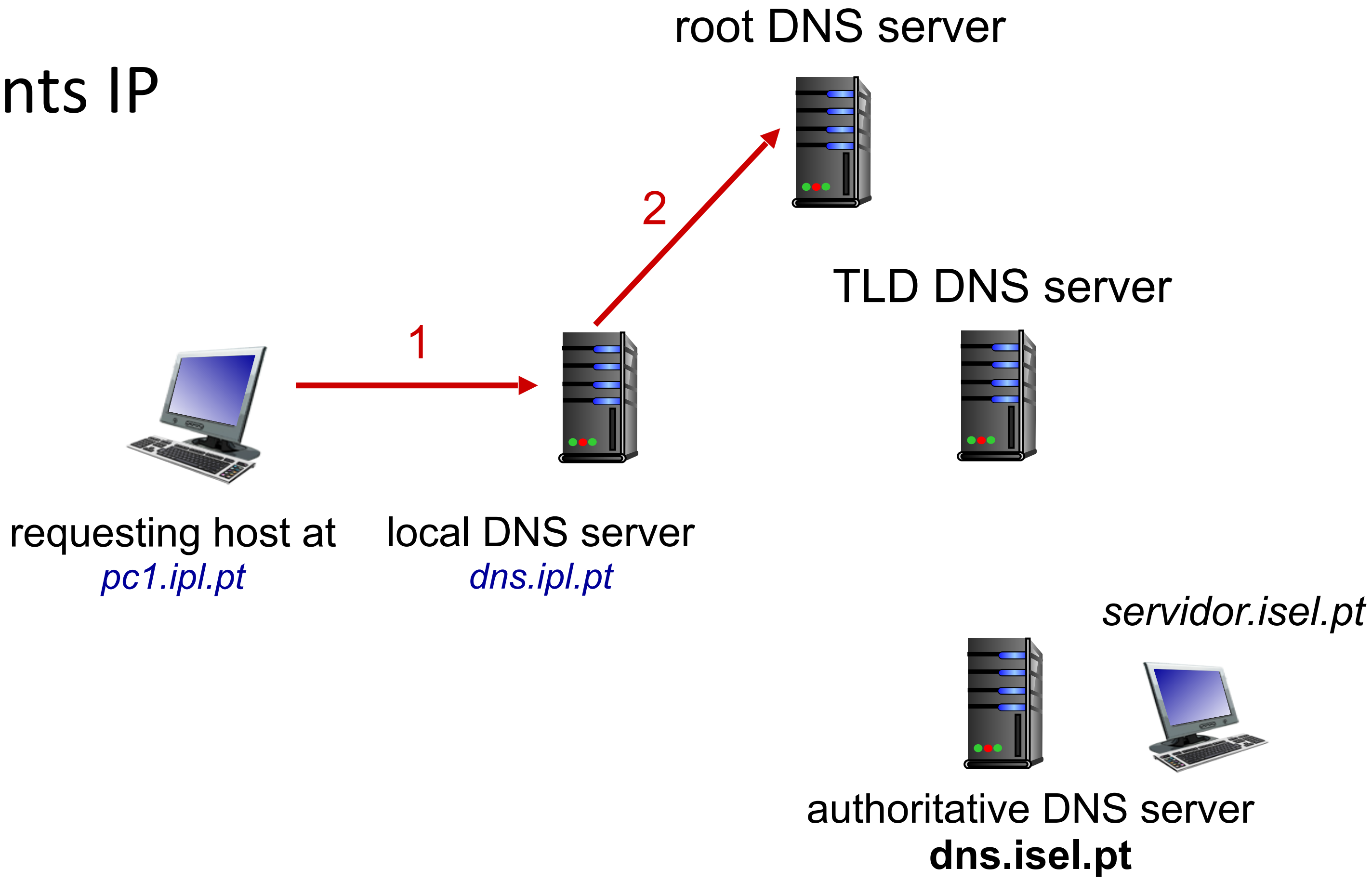

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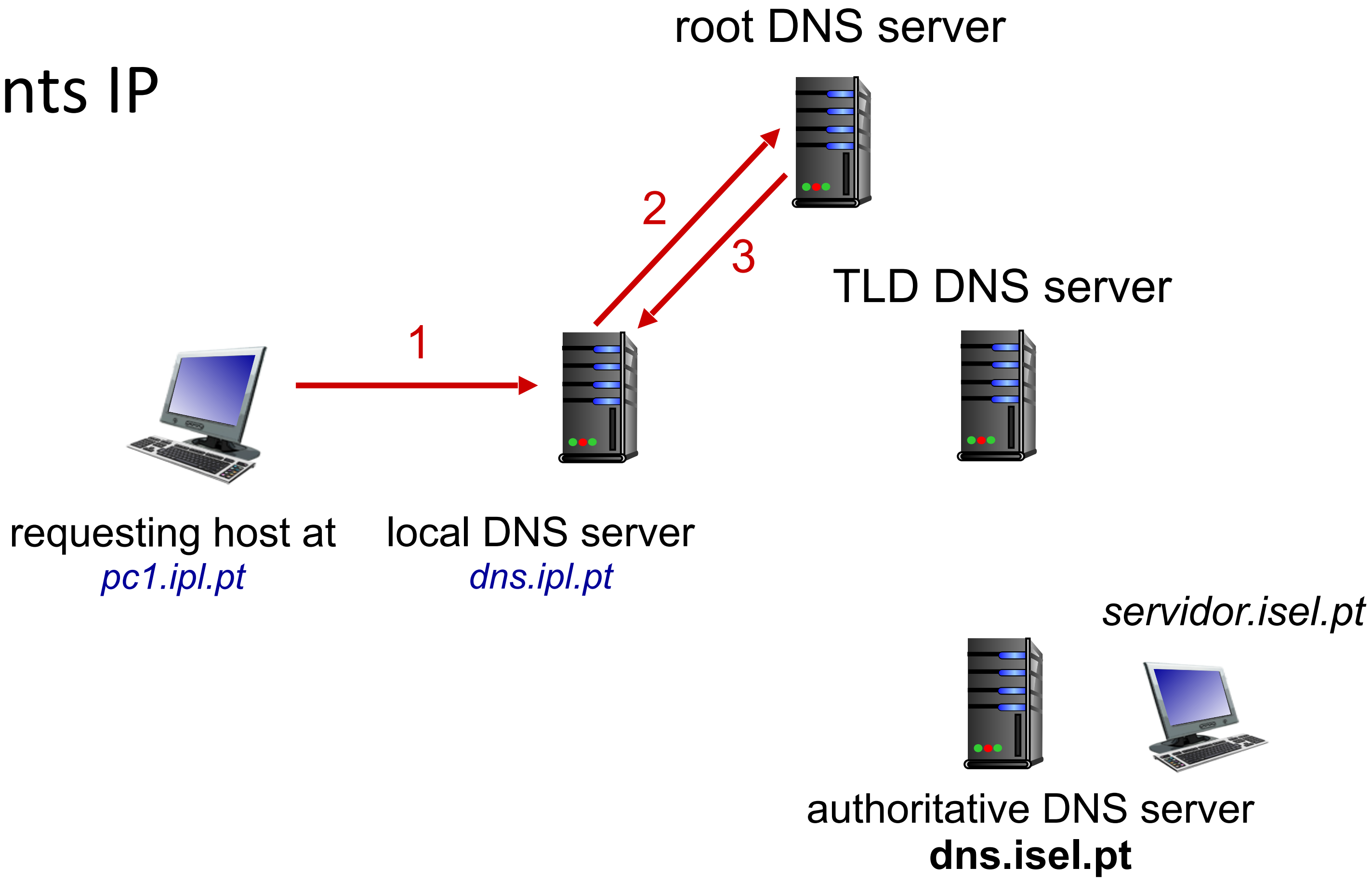

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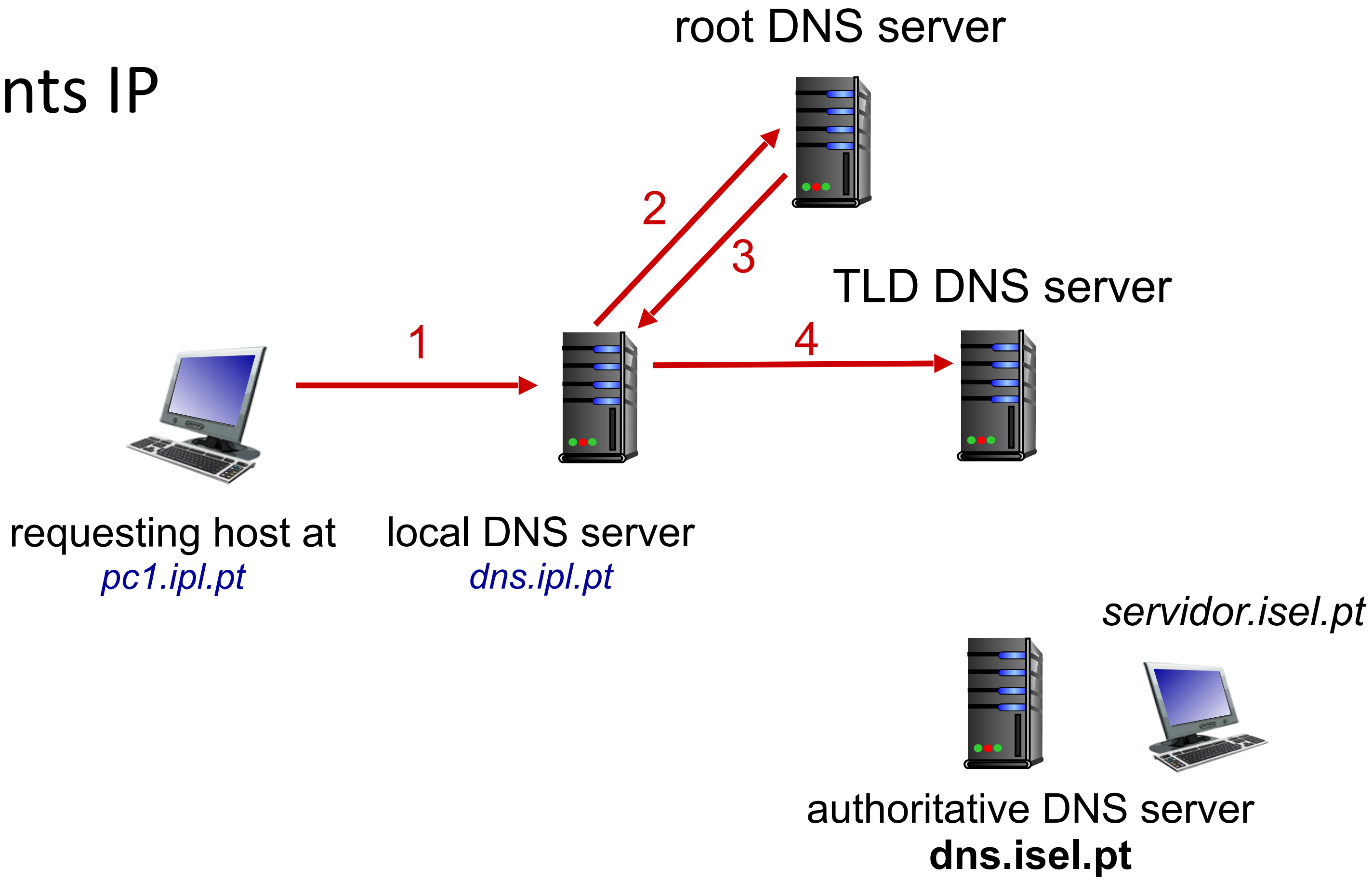

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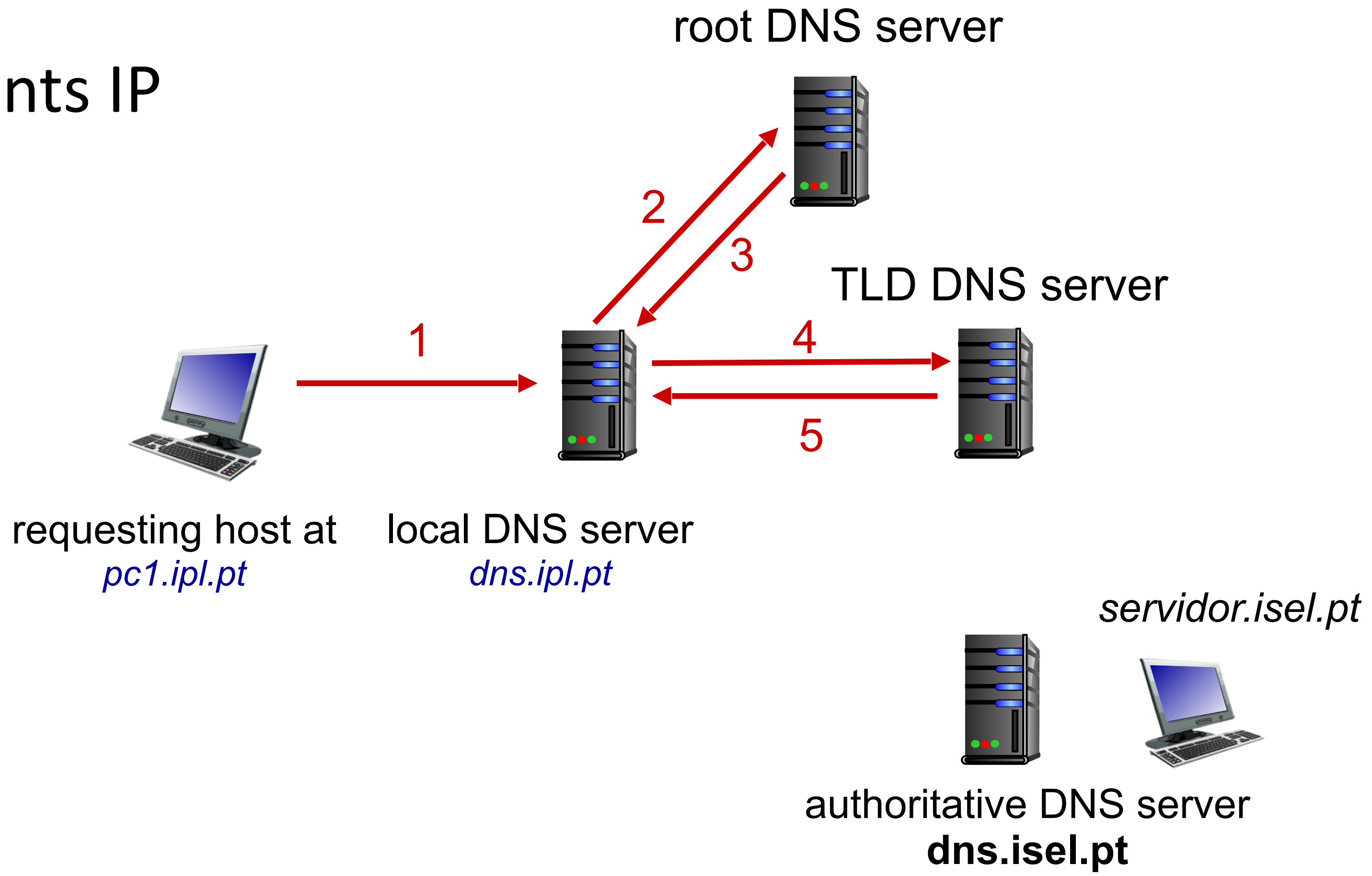

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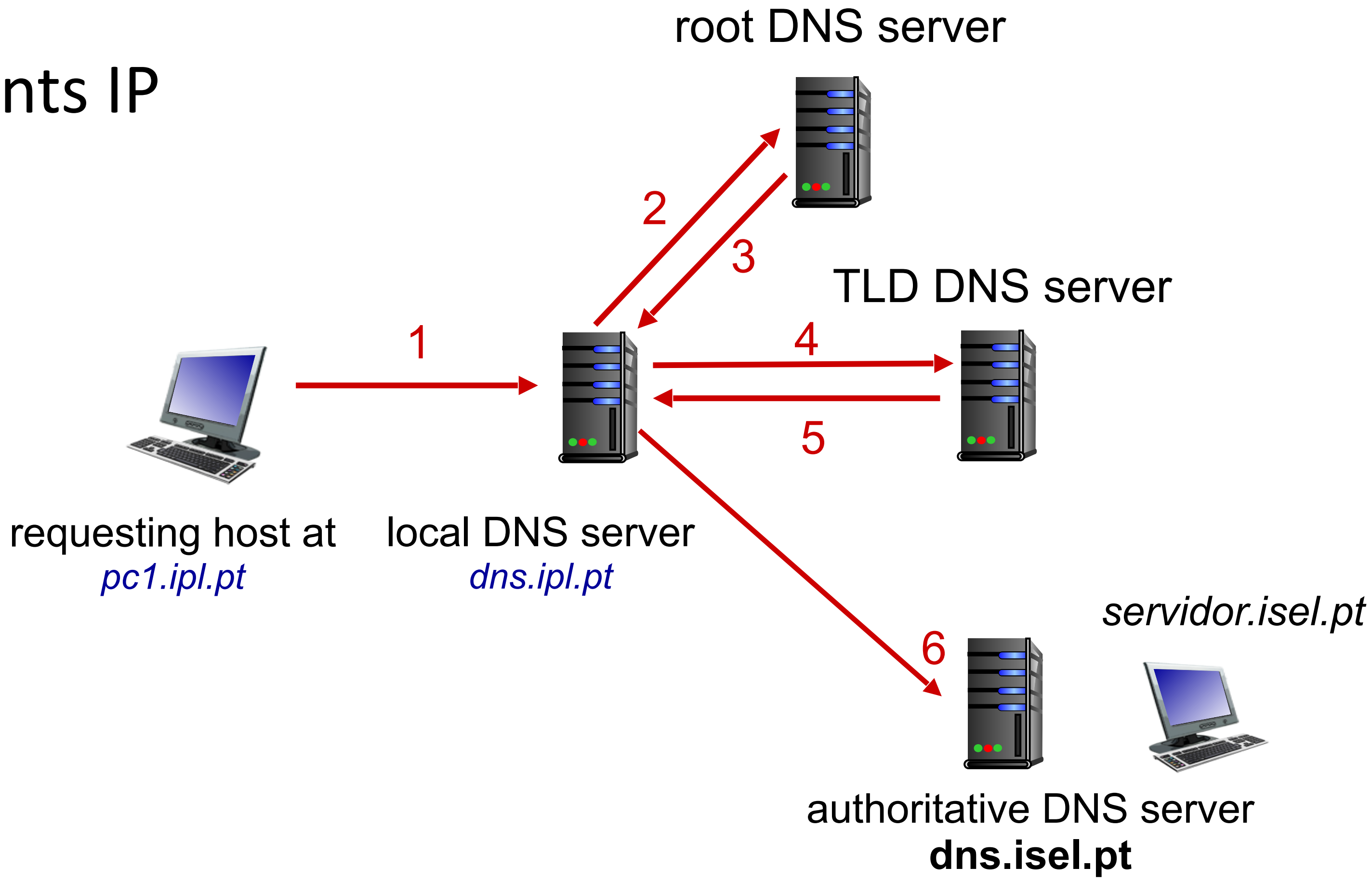

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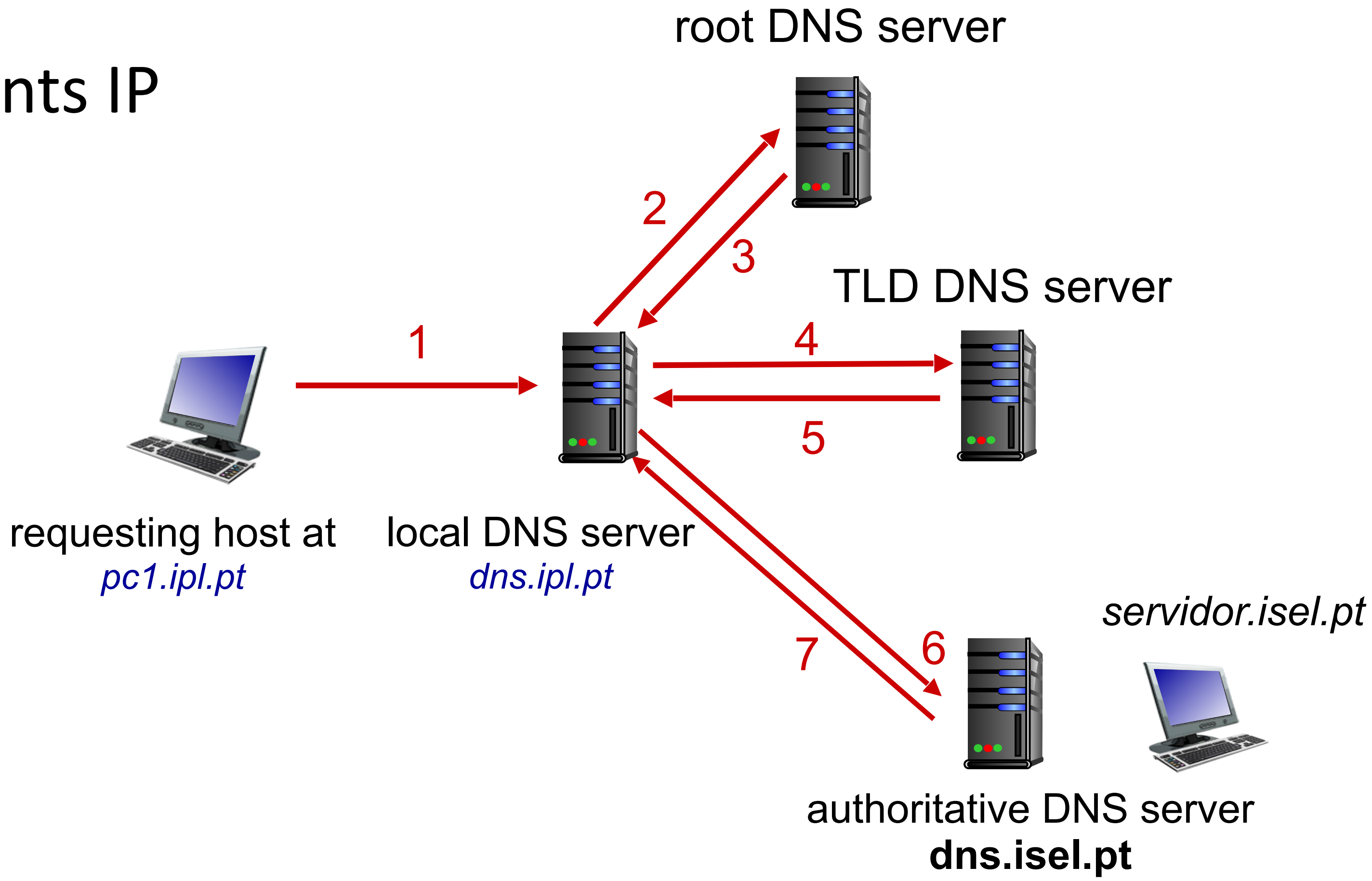

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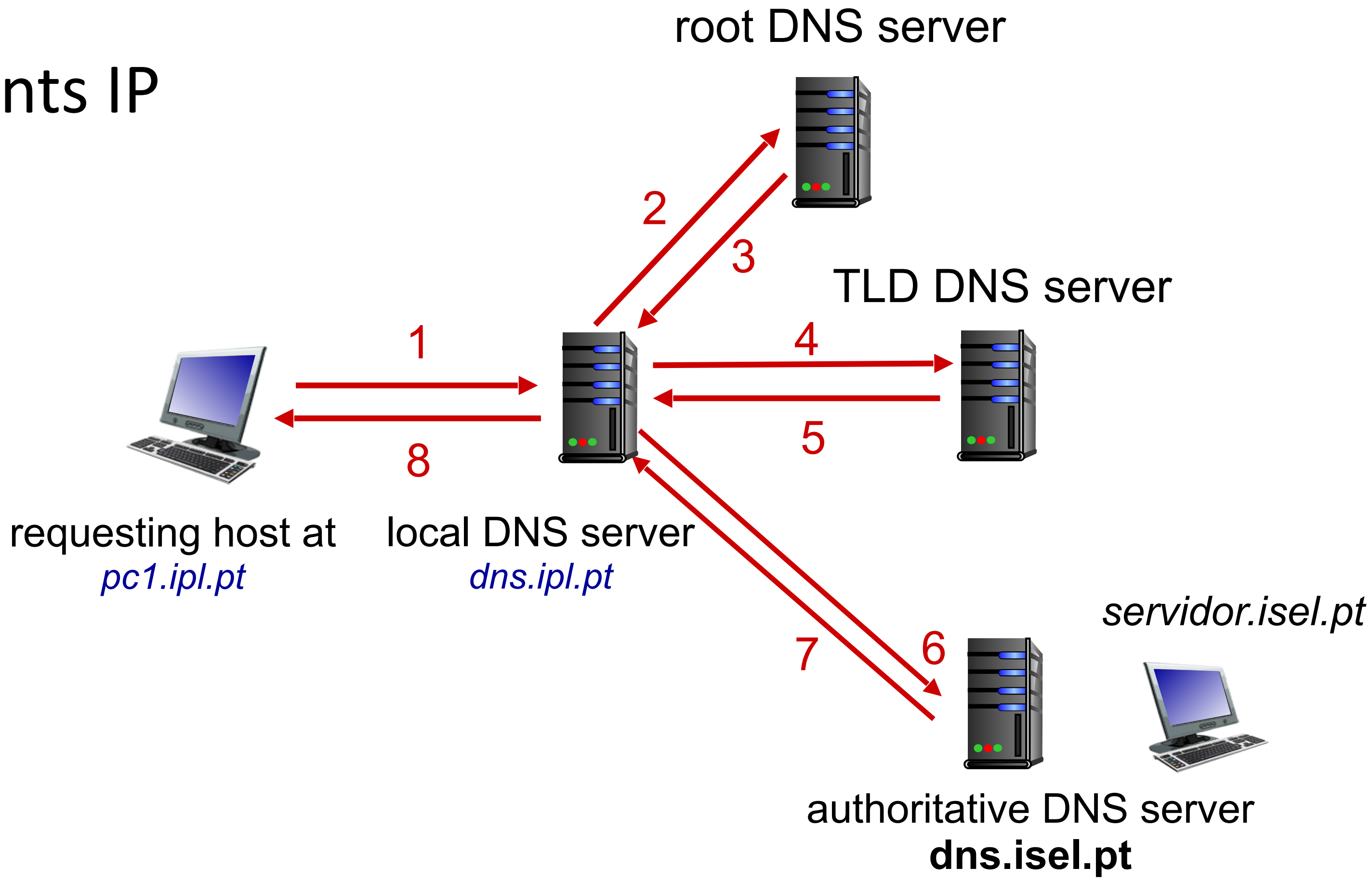

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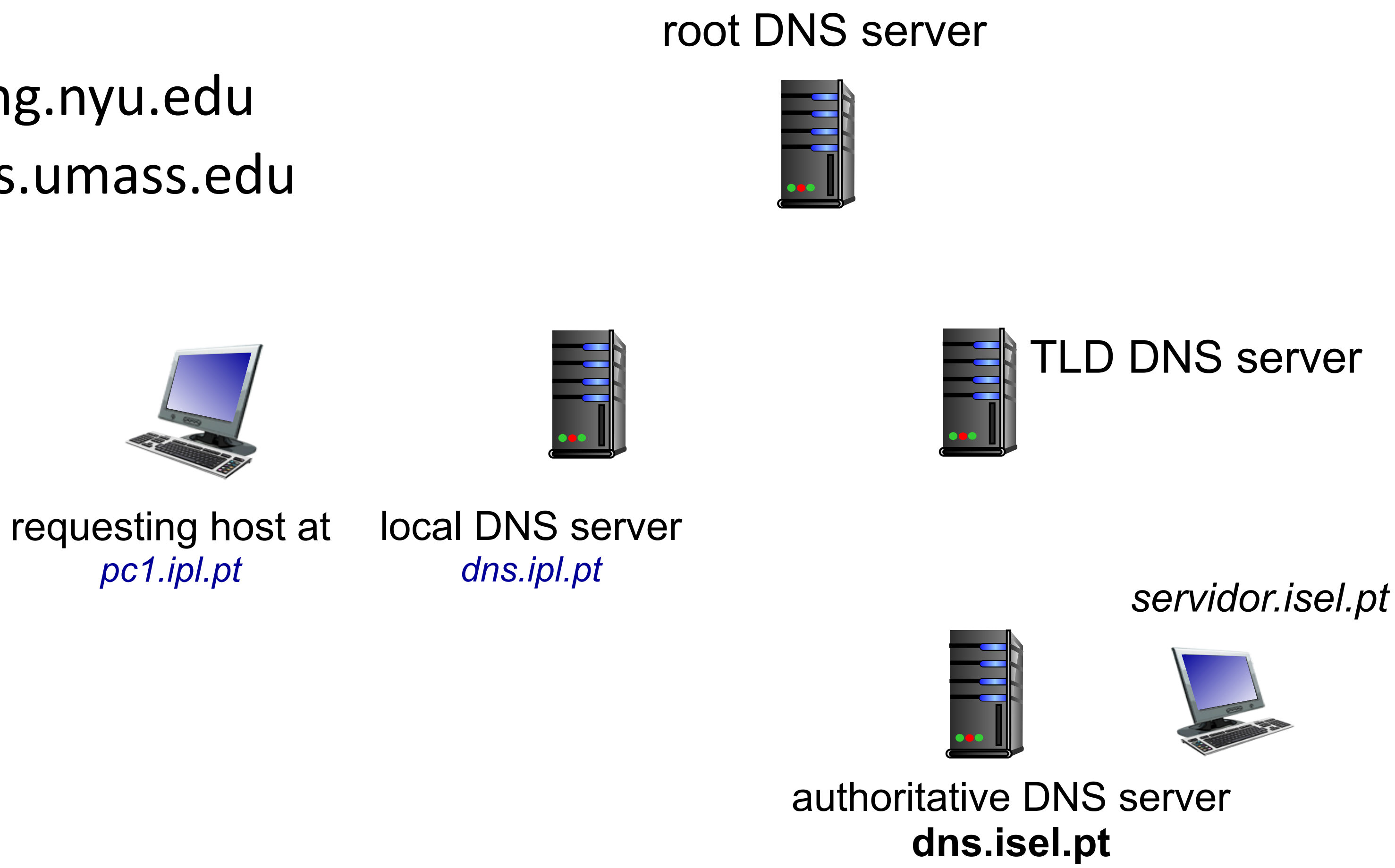

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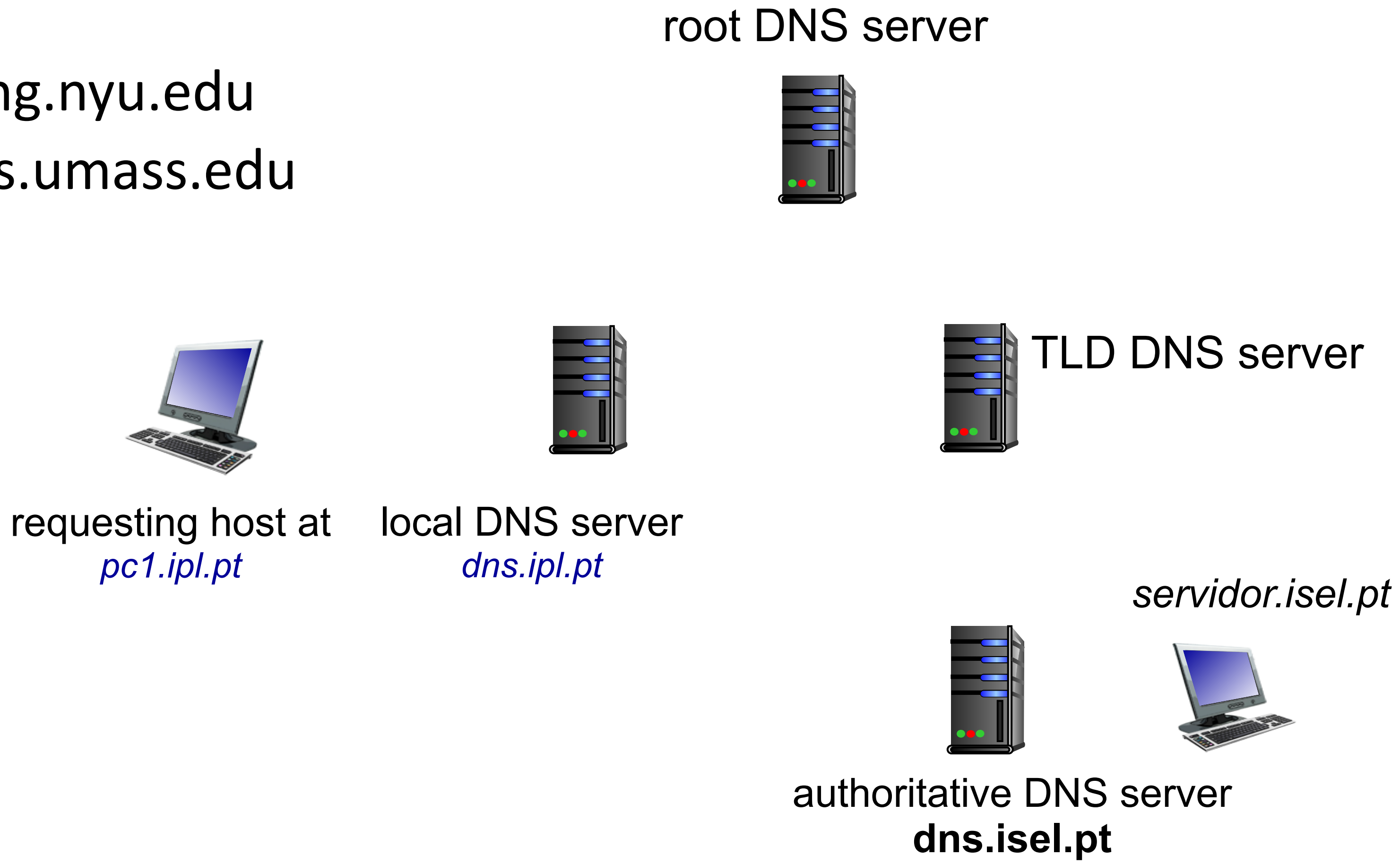

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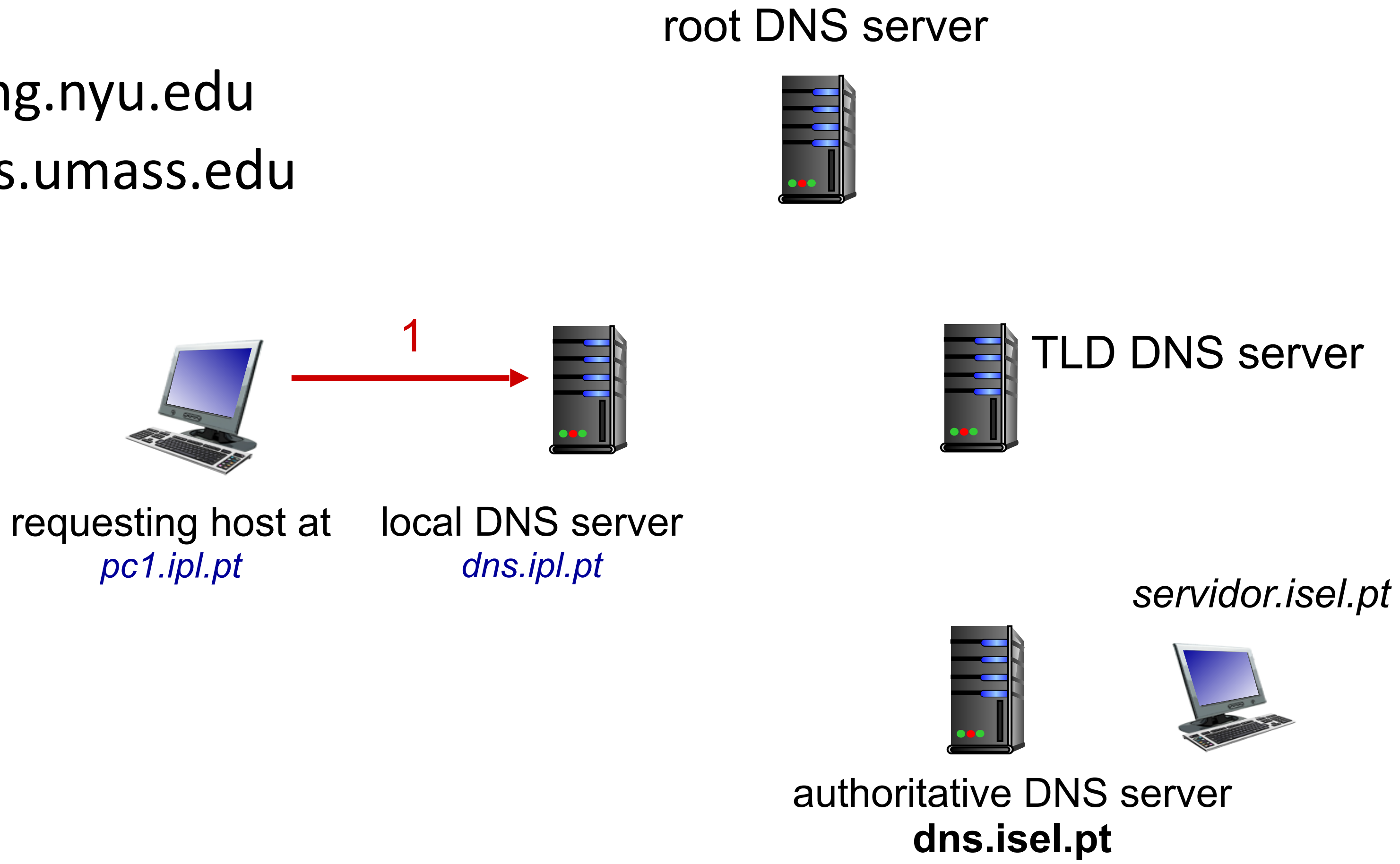

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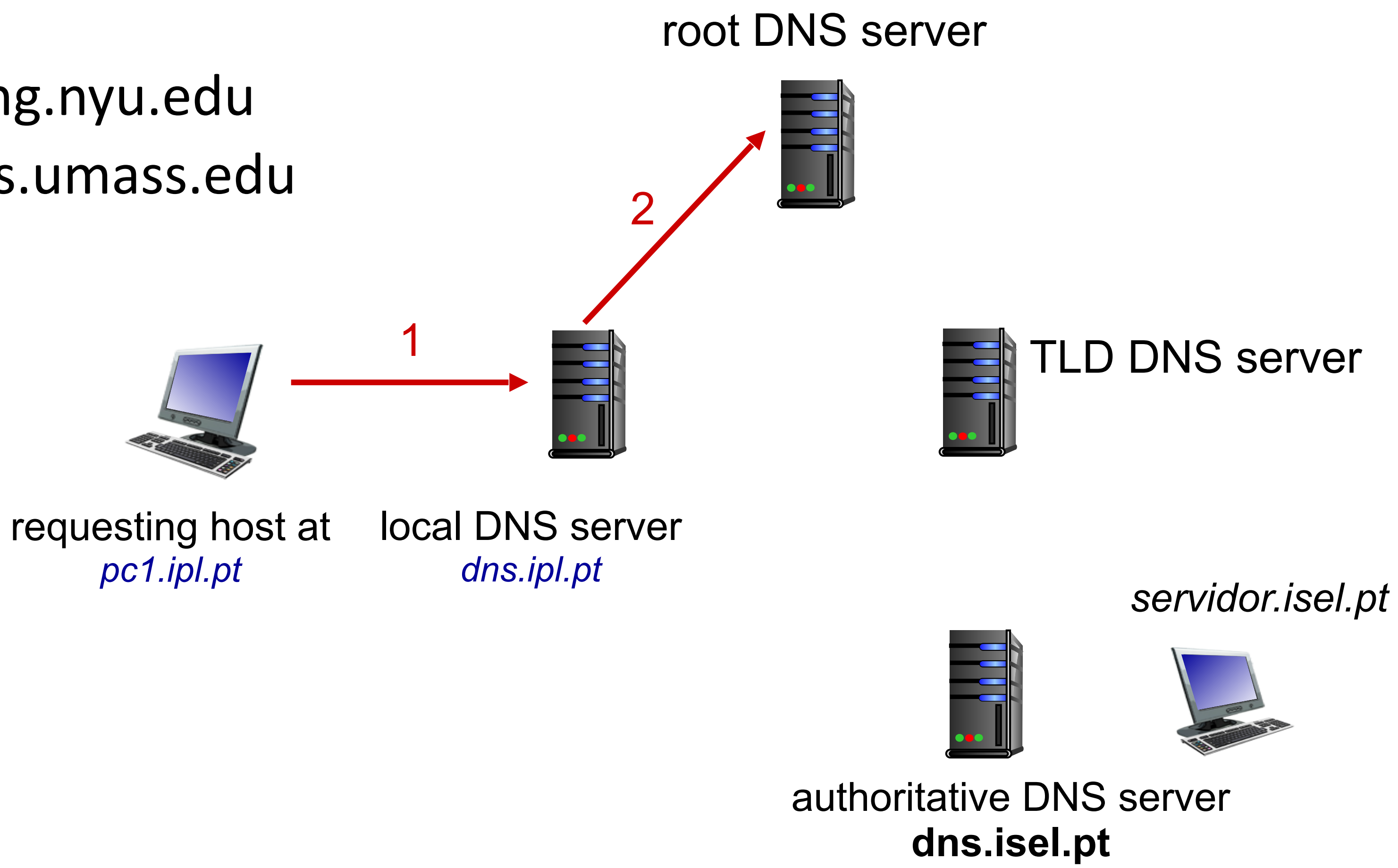

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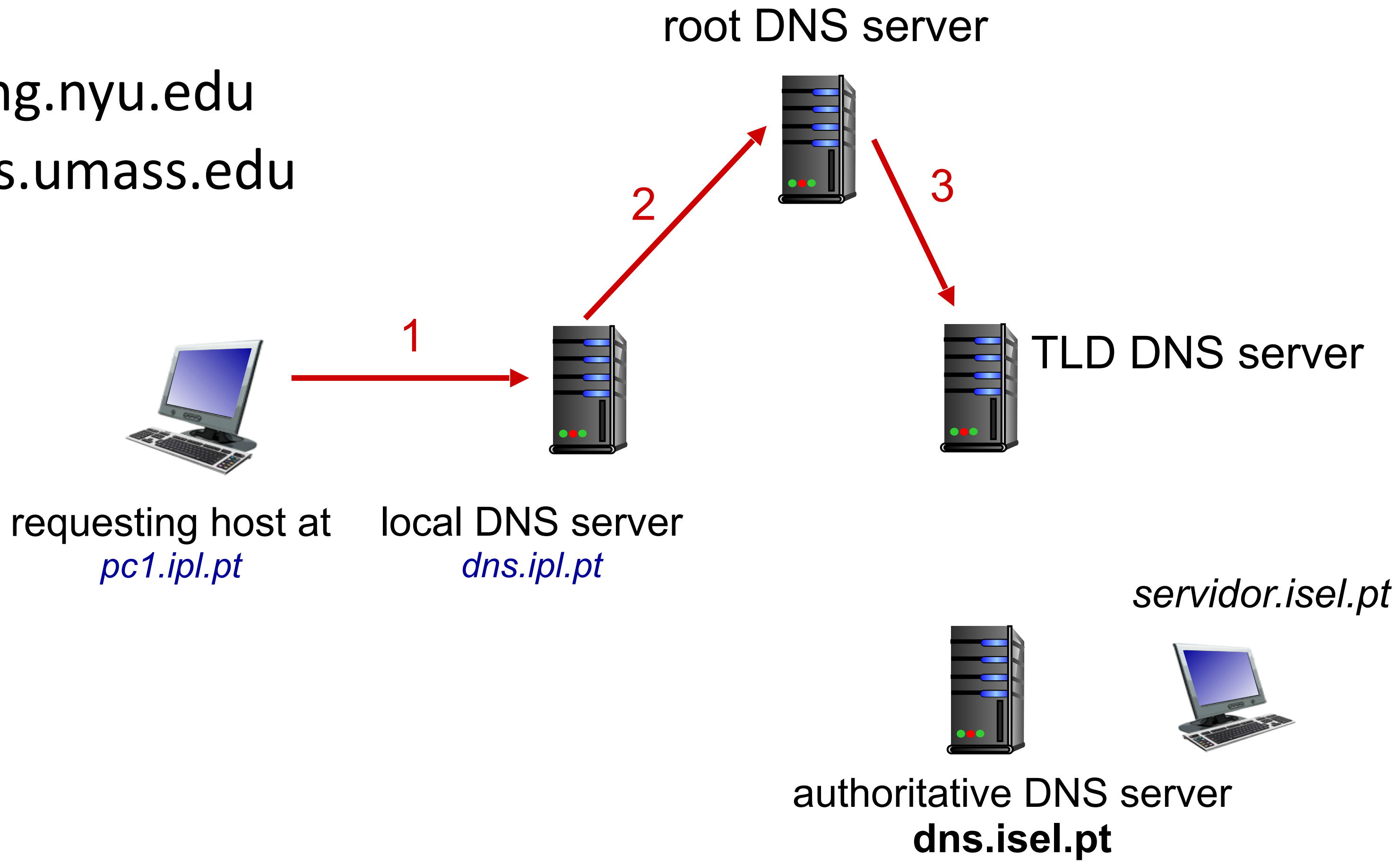

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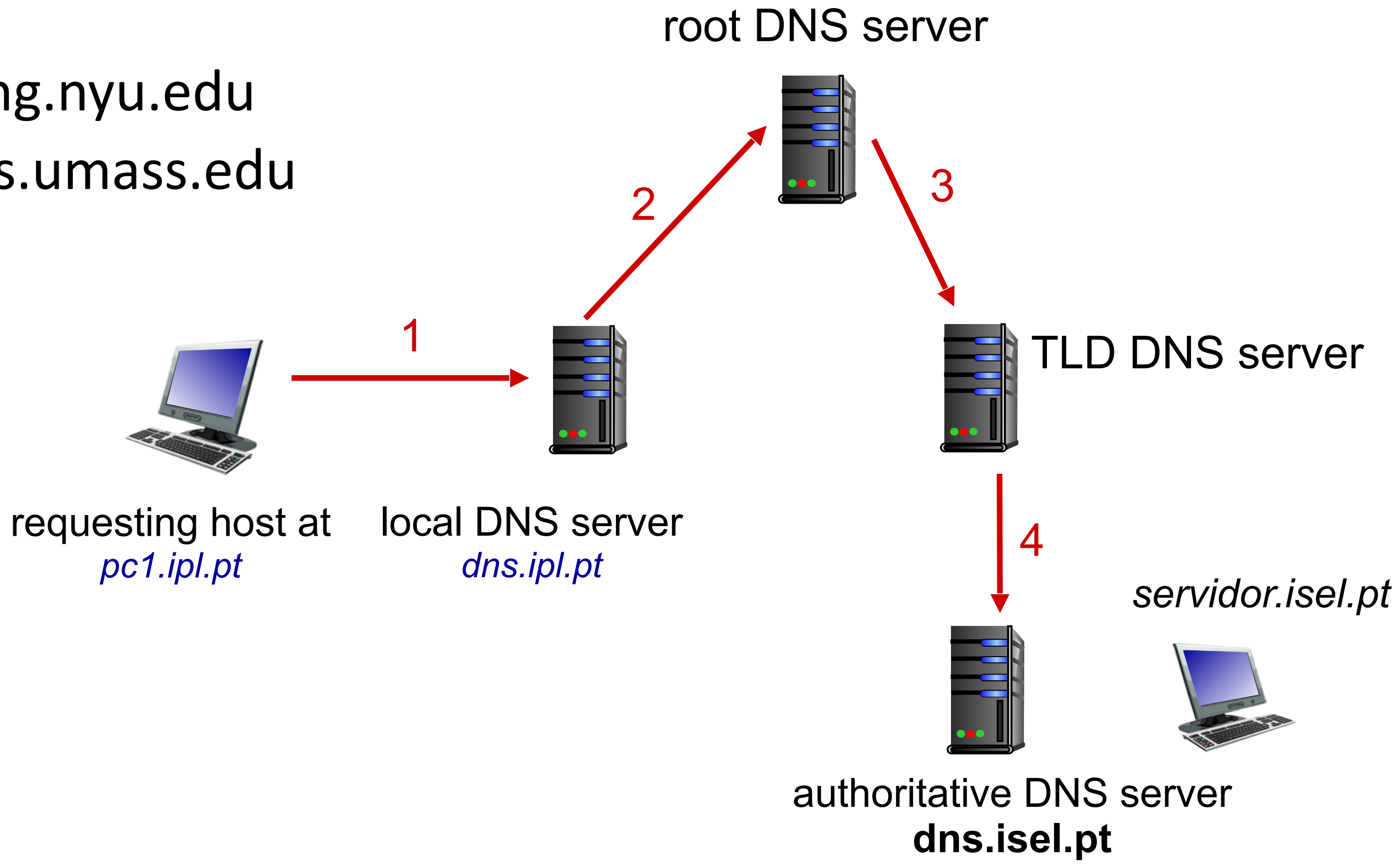

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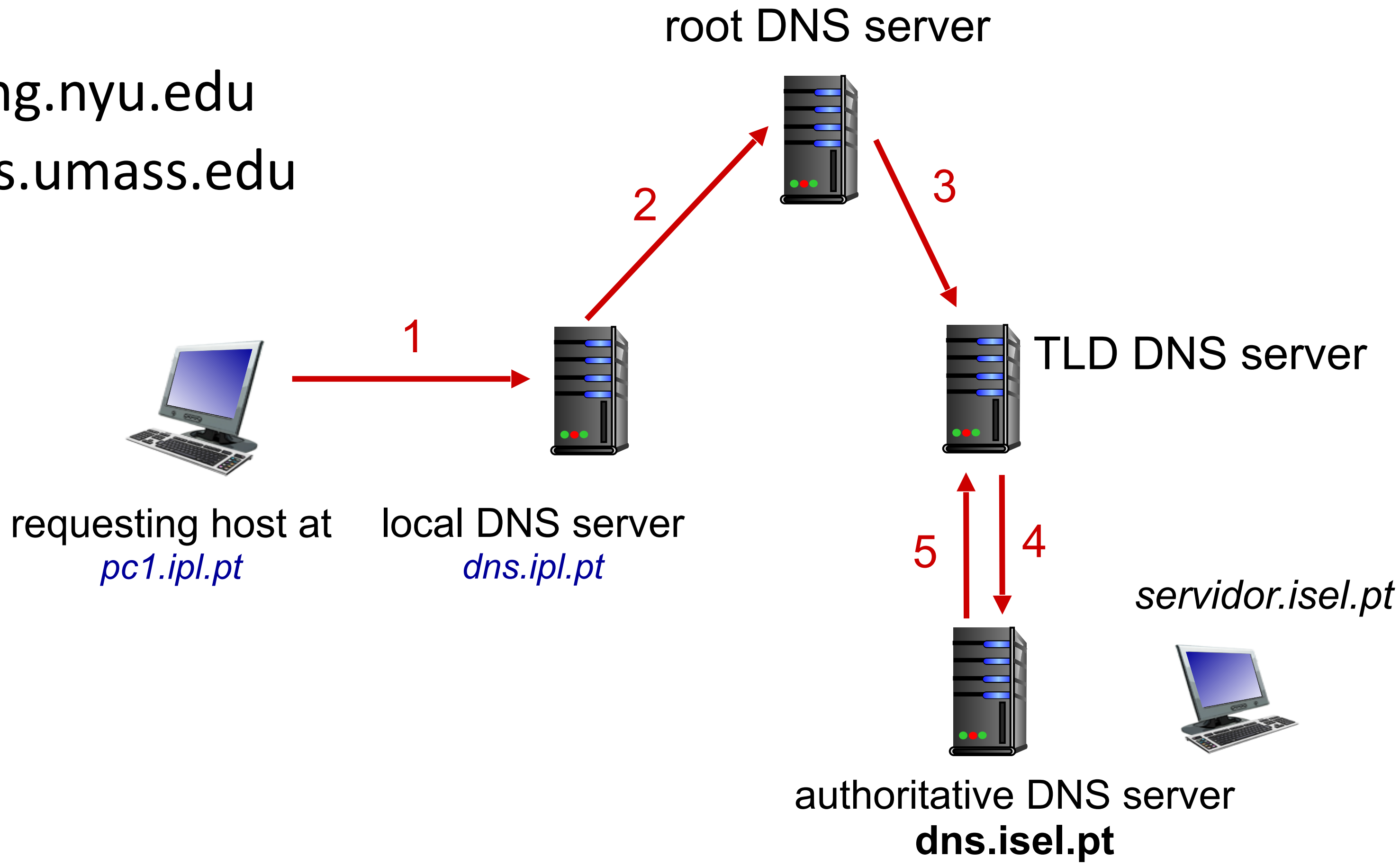

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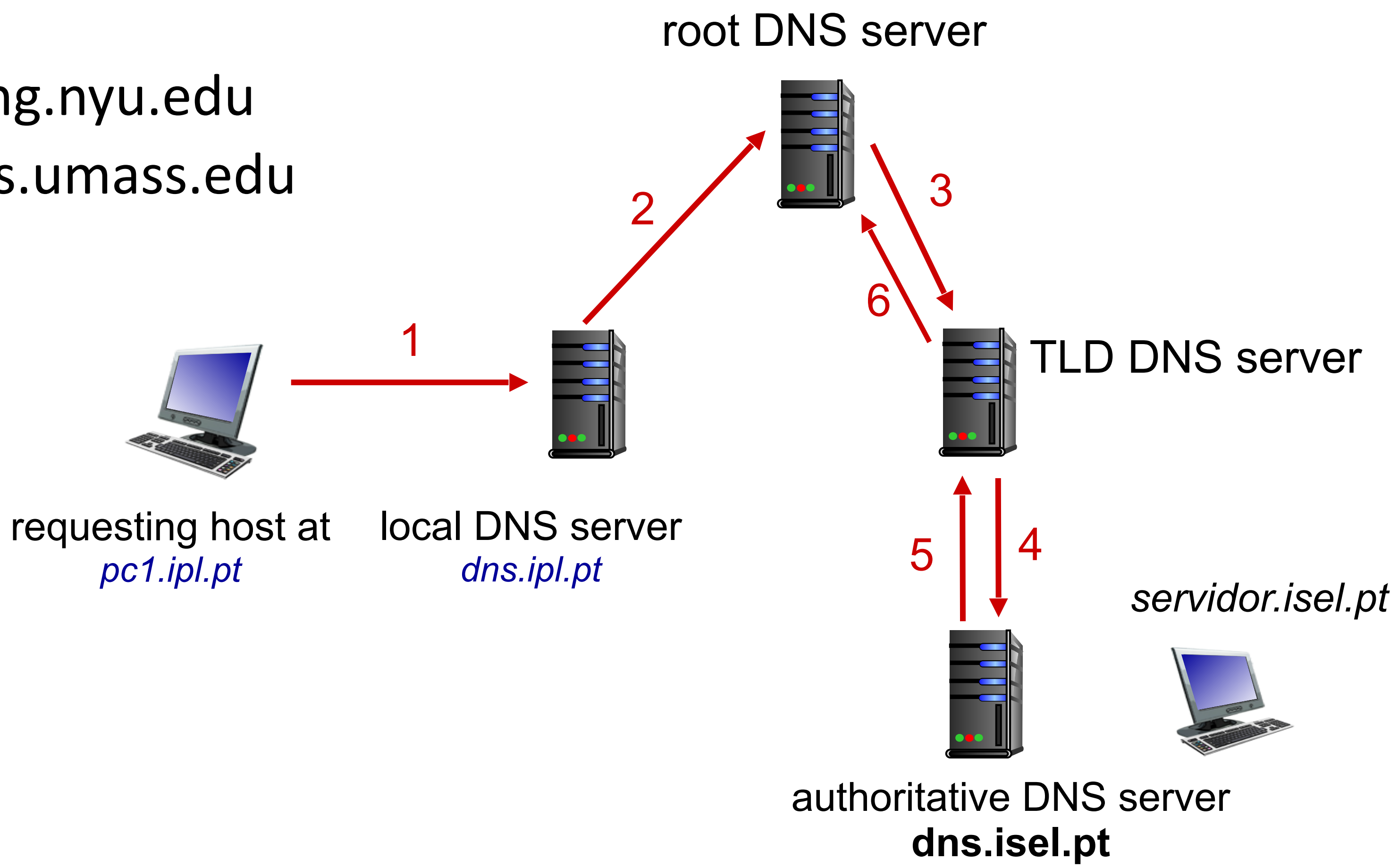

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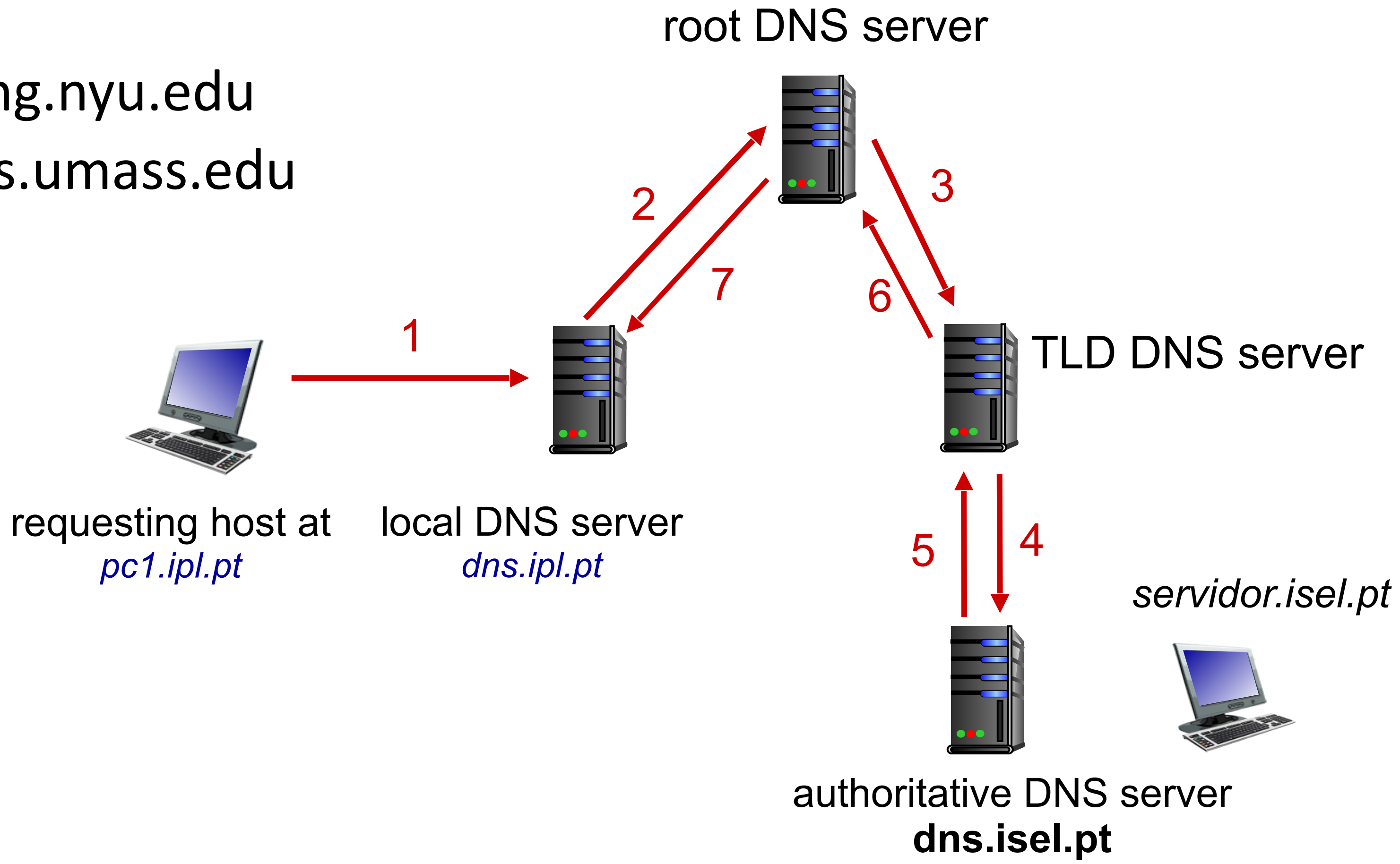

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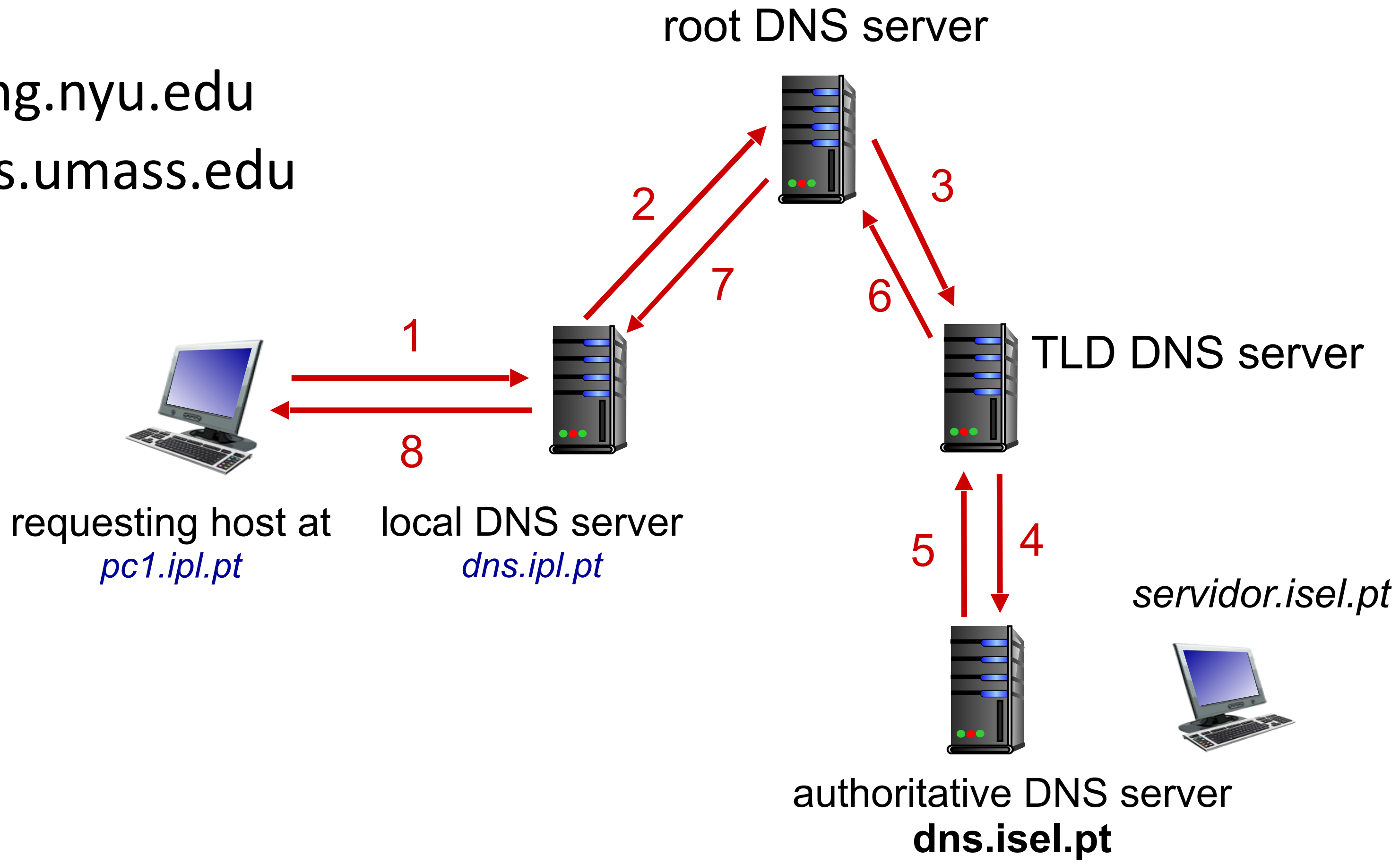

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type=MX

- `value` is name of SMTP mail server associated with `name`

DNS protocol messages

DNS *query* and *reply* messages, both have same *format:*

message header:

← 2 bytes →	← 2 bytes →
identification	flags
# questions	# answer RRs
# authority RRs	# additional RRs
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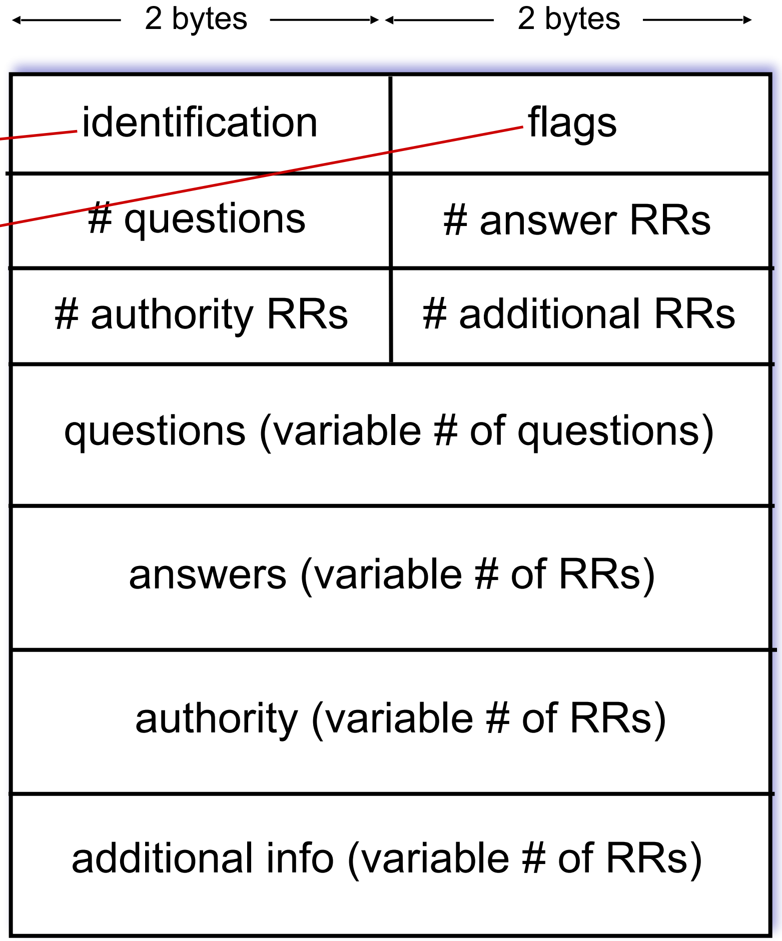
  - reply is authoritative



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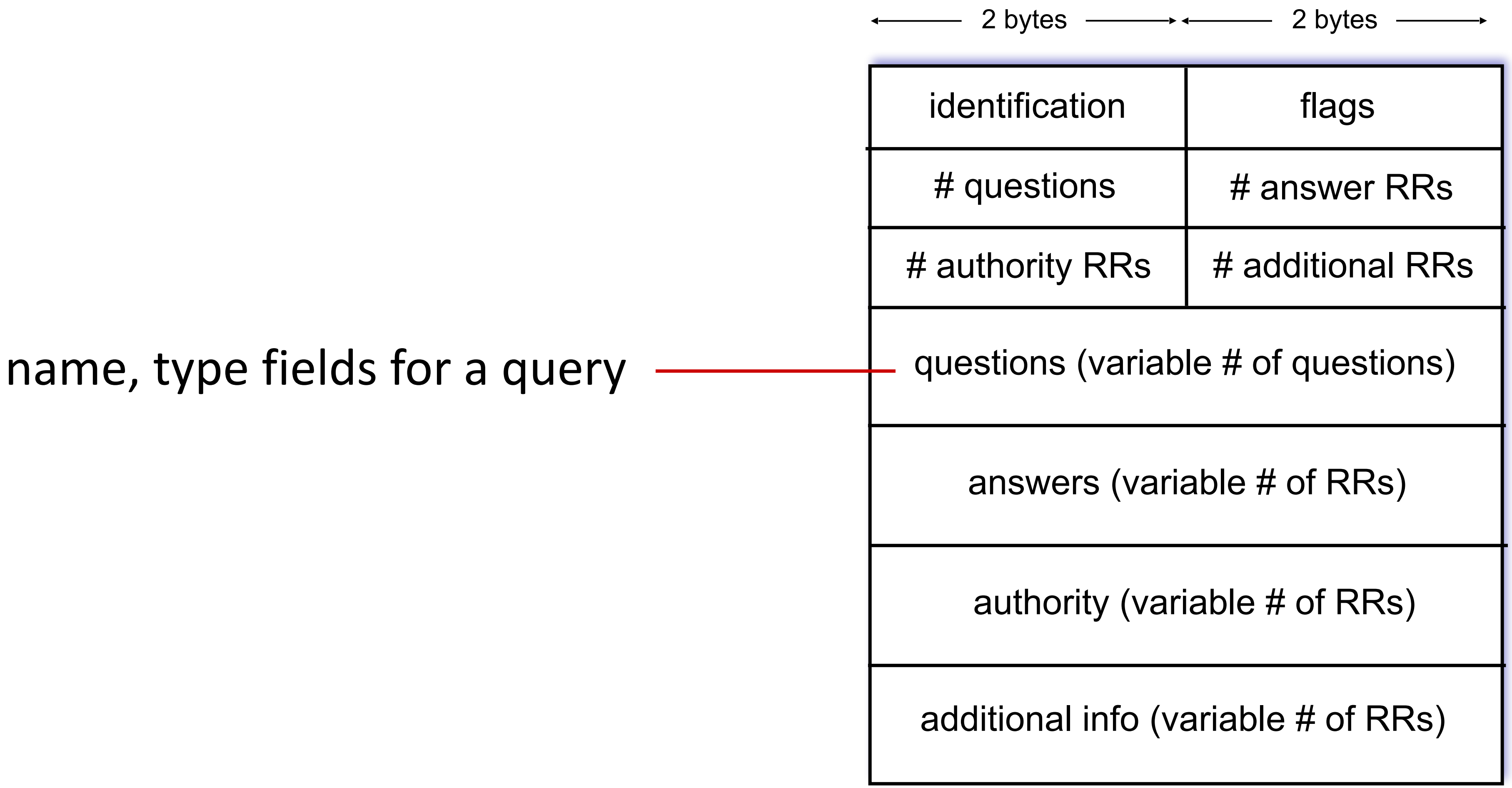

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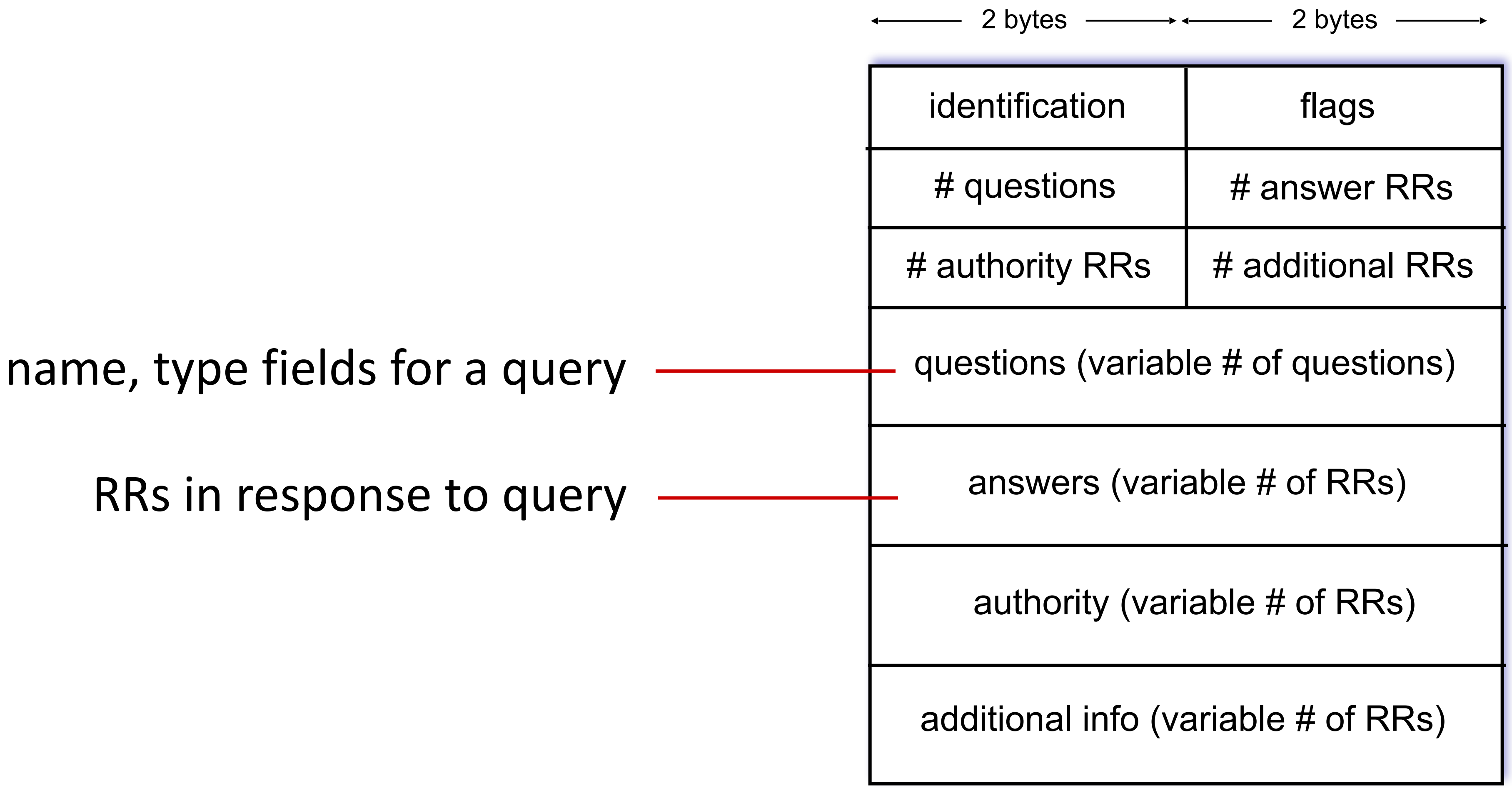

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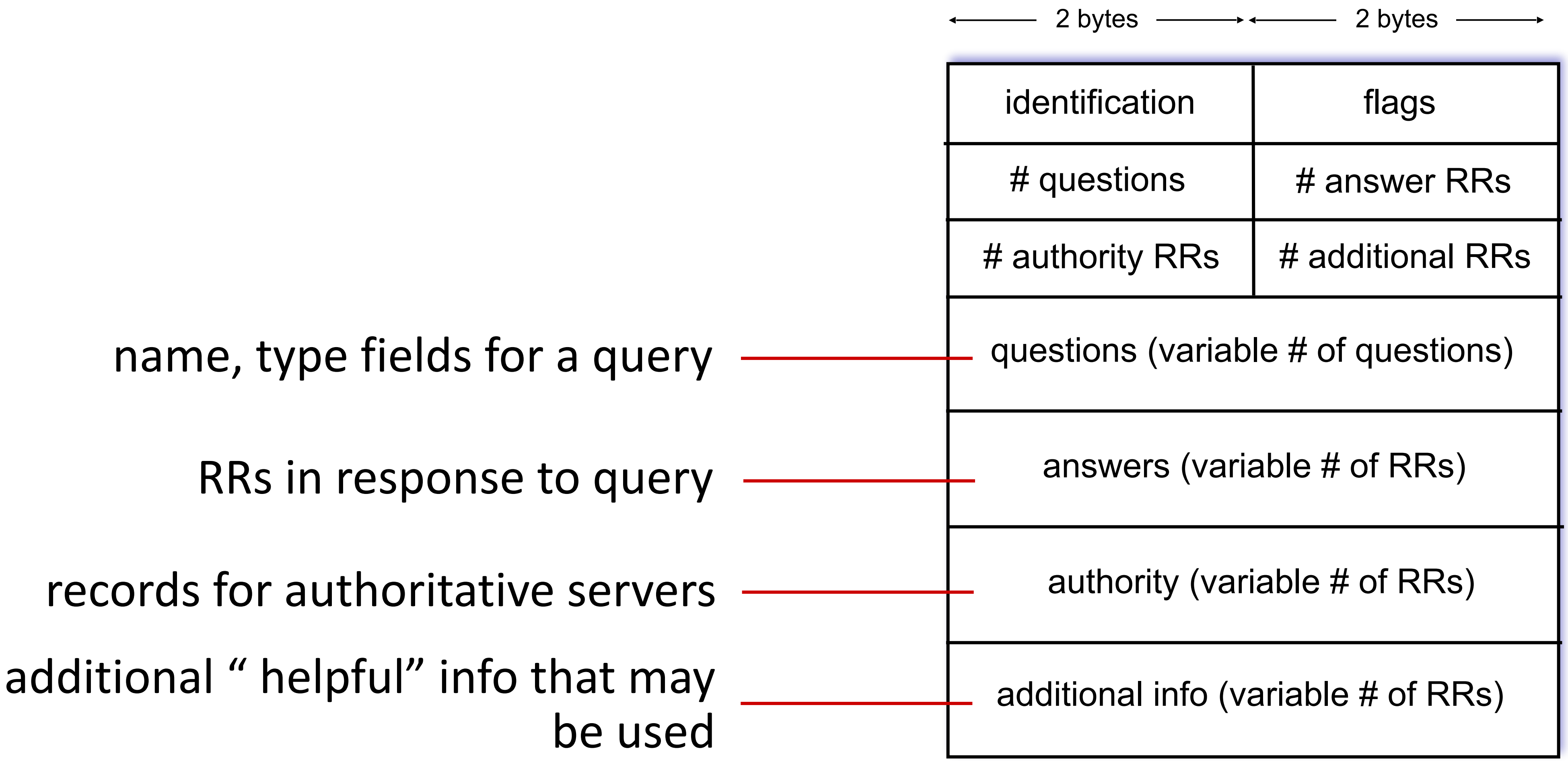

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- register name networkuptopia.com at *DNS registrar* (e.g., Network Solutions)
  - provide names, IP addresses of authoritative name server (primary and secondary)
  - registrar inserts NS, A RRs into .com TLD server:

```
(networkutopia.com, dns1.networkutopia.com, NS)
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DNS security

DDoS attacks

- bombard root servers with traffic
  - not successful to date
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Spoofing attacks

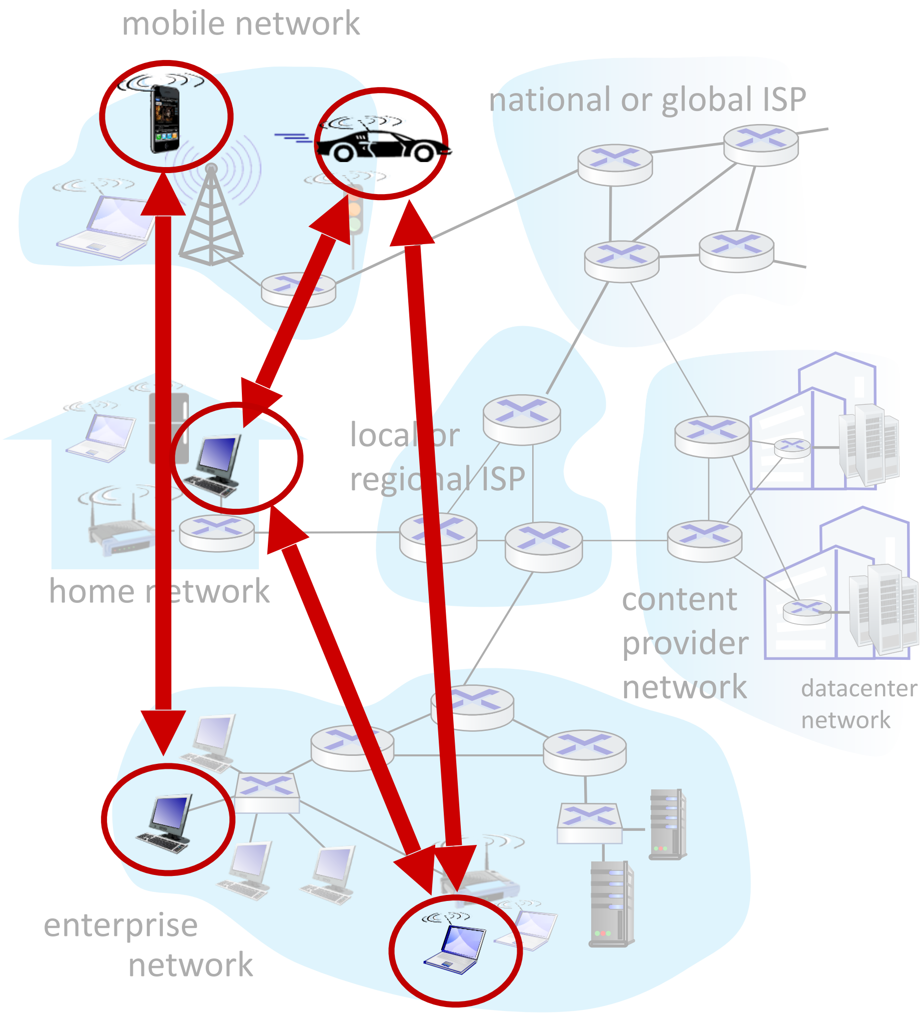
- intercept DNS queries, returning bogus replies
  - DNS cache poisoning
  - RFC 4033: DNSSEC authentication services

Chapter 2: outline

- Principles of network applications
- Web and HTTP
- Electronic mail (E-mail)
  - SMTP, POP3, IMAP
- The Domain Name System (DNS)
- P2P applications
- Video streaming and content distribution networks

Peer-to-peer (P2P) architecture

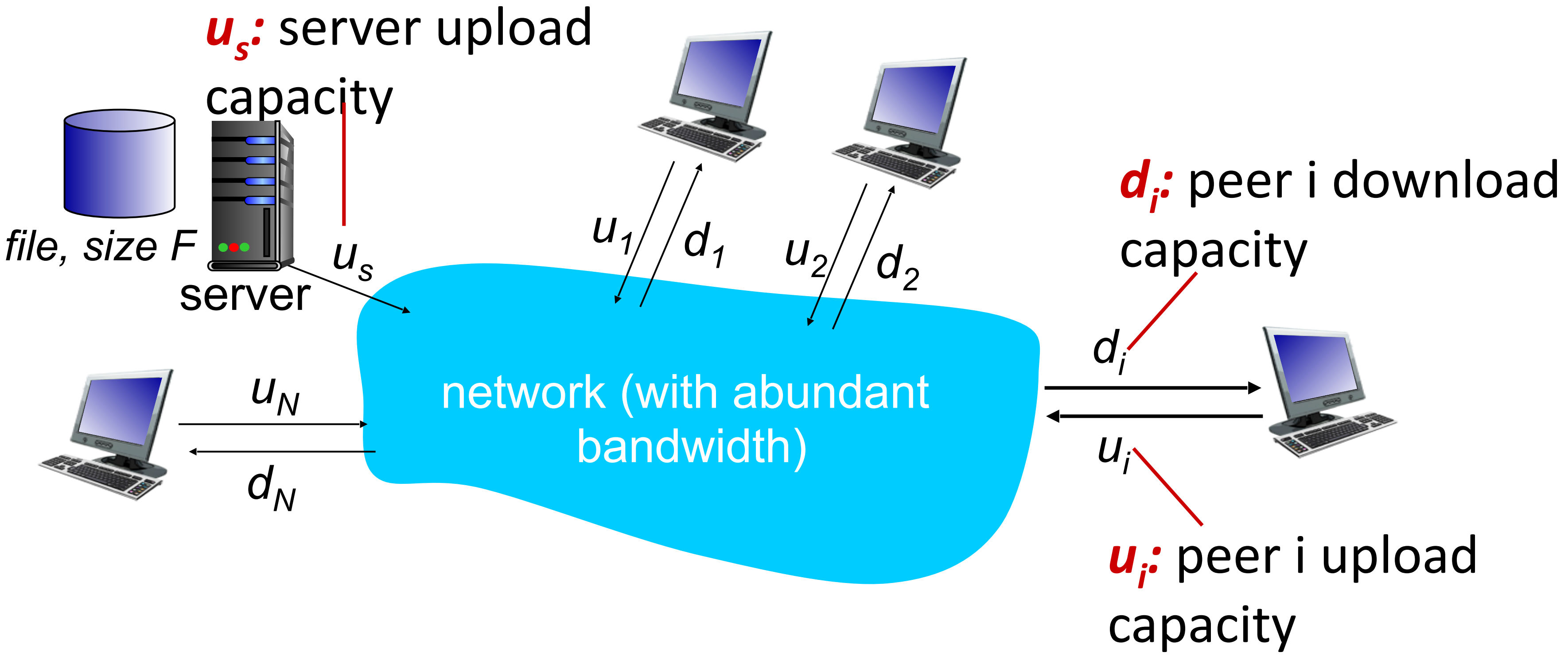
- *no* always-on server
- arbitrary end systems directly communicate
- peers request service from other peers, provide service in return to other peers
  - *self scalability* – new peers bring new service capacity, and new service demands
- peers are intermittently connected and change IP addresses
  - complex management
- examples: P2P file sharing (BitTorrent), streaming (KanKan), VoIP (Skype)



File distribution: client-server vs P2P

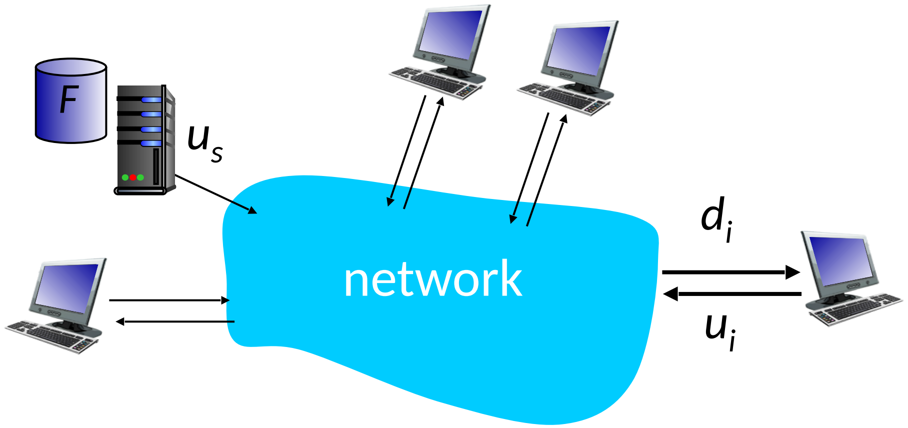
Q: how much time to distribute file (size *F*) from one server to *N peers*?

- peer upload/download capacity is limited resource



File distribution time: client-server

- *server transmission:* must sequentially send (upload) N file copies:
  - time to send one copy: F/u_s
  - time to send N copies: NF/u_s



- *client:* each client must download file copy
  - d_{min} = min client download rate
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time to distribute F to N clients using client-server approach

$$D_{c\text{-}s} \geq max\{NF/u_s, F/d_{min}\}$$

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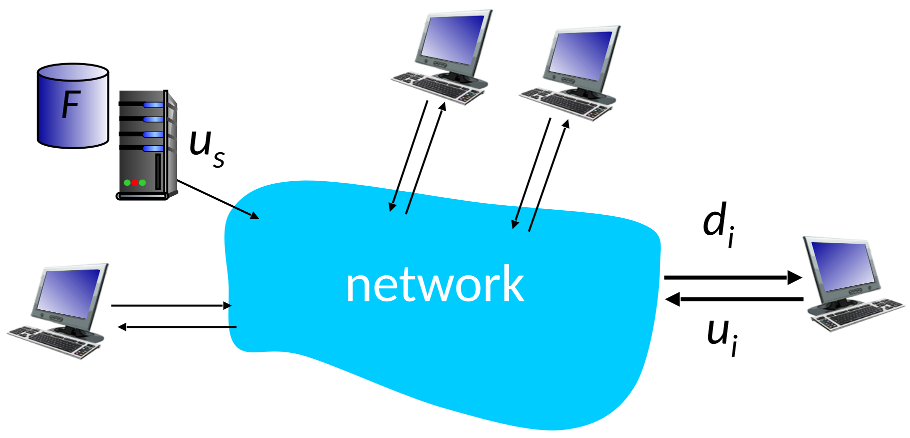

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File distribution time: P2P

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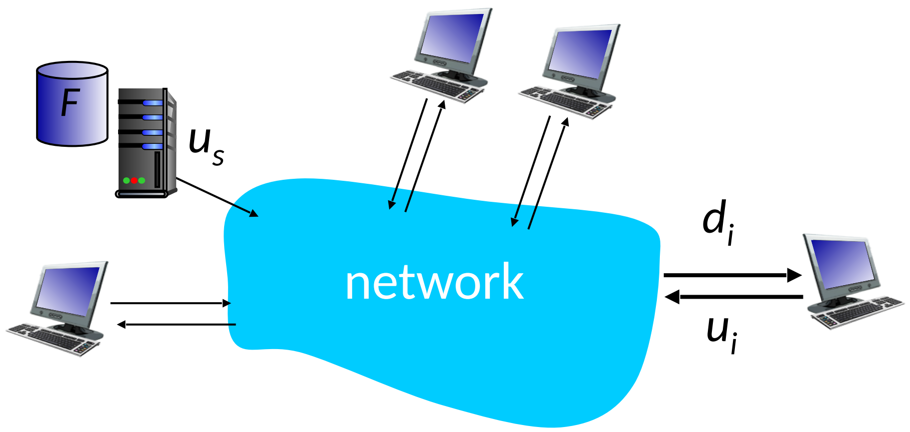
  - max upload rate (limiting max download rate) is $u_s + \Sigma u_i$



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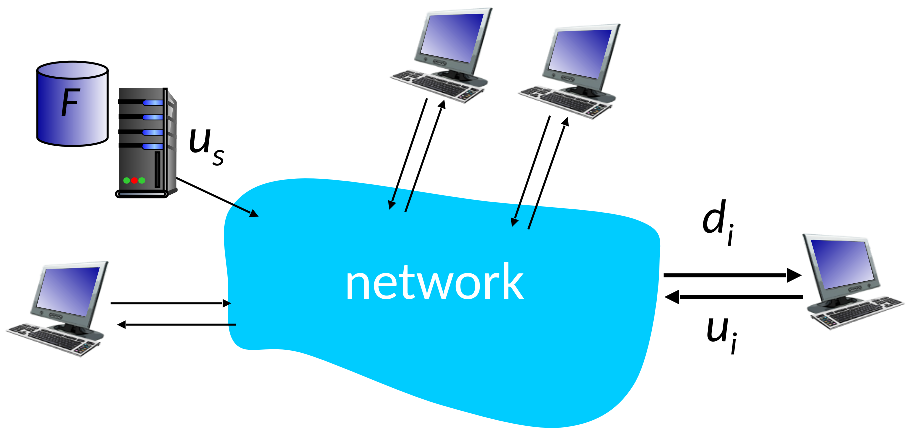

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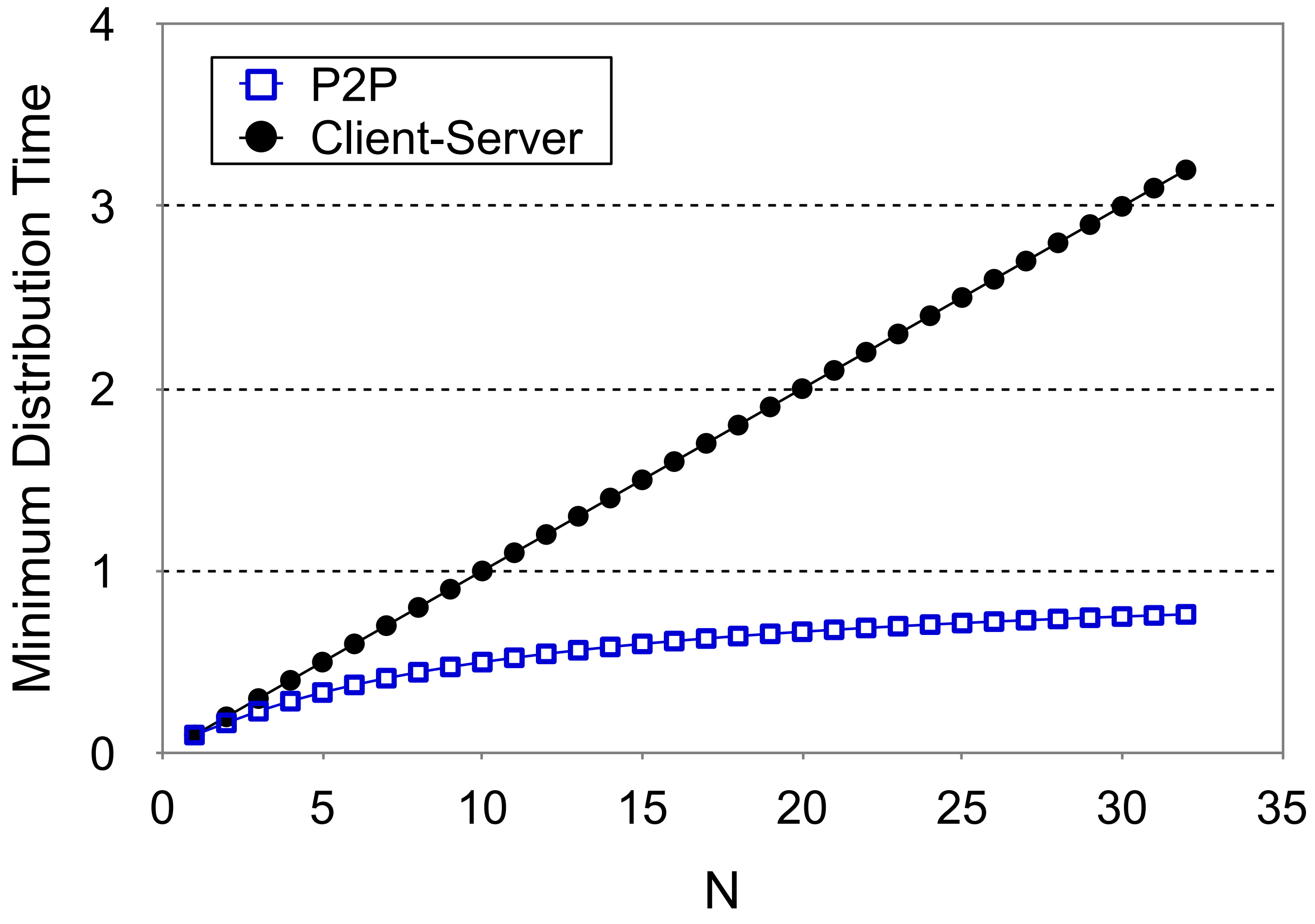
increases linearly in *N* …

… but so does this, as each peer brings service capacity

Client-server vs. P2P: example

client upload rate = u, F/u = 1 hour, $u_s = 10u$, $d_{min} \geq u_s$

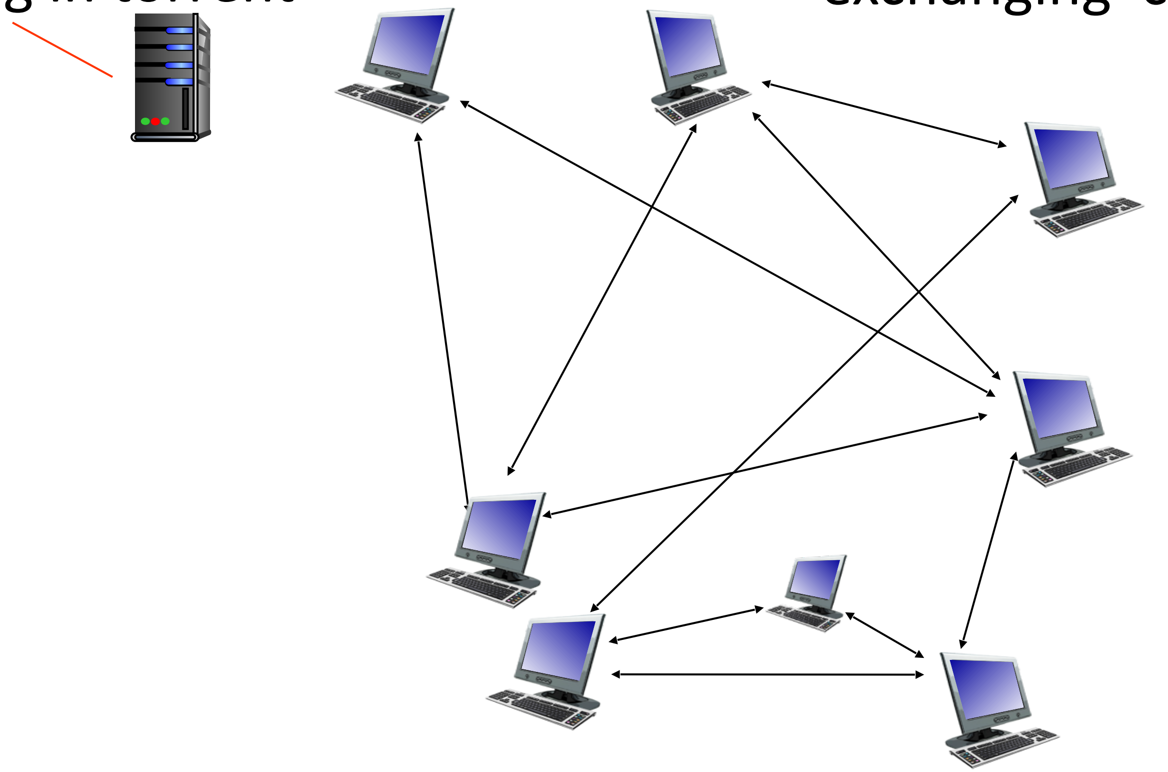


P2P file distribution: BitTorrent

- file divided into 256Kb chunks
- peers in torrent send/receive file chunks

tracker: tracks peers participating in torrent

torrent: group of peers exchanging chunks of a file



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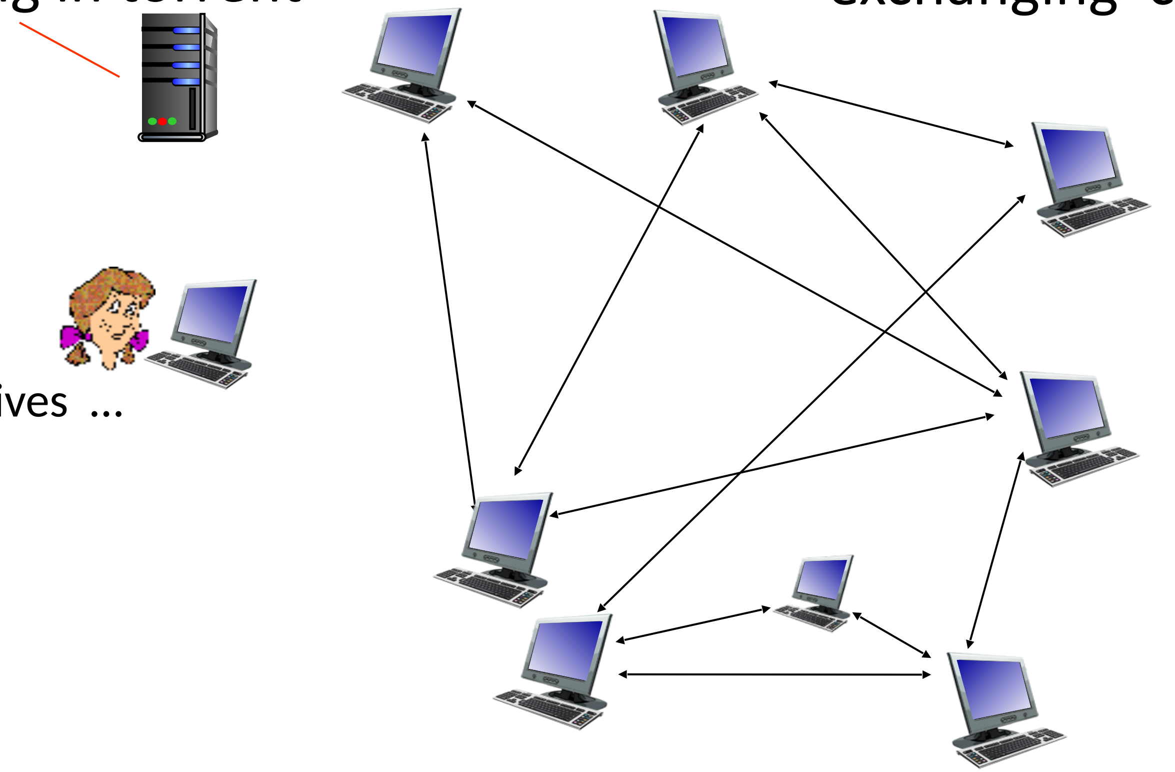

Alice arrives …

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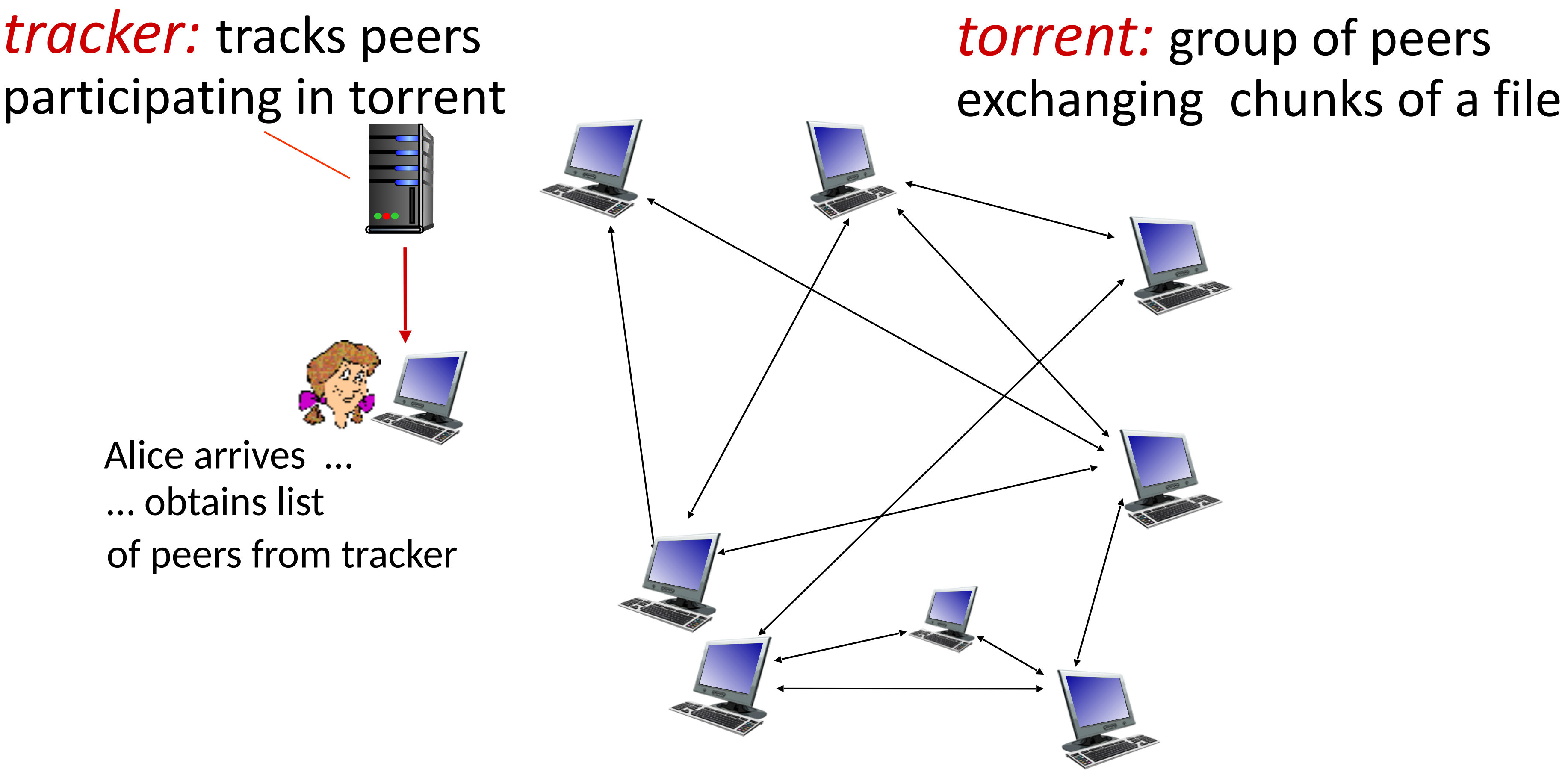

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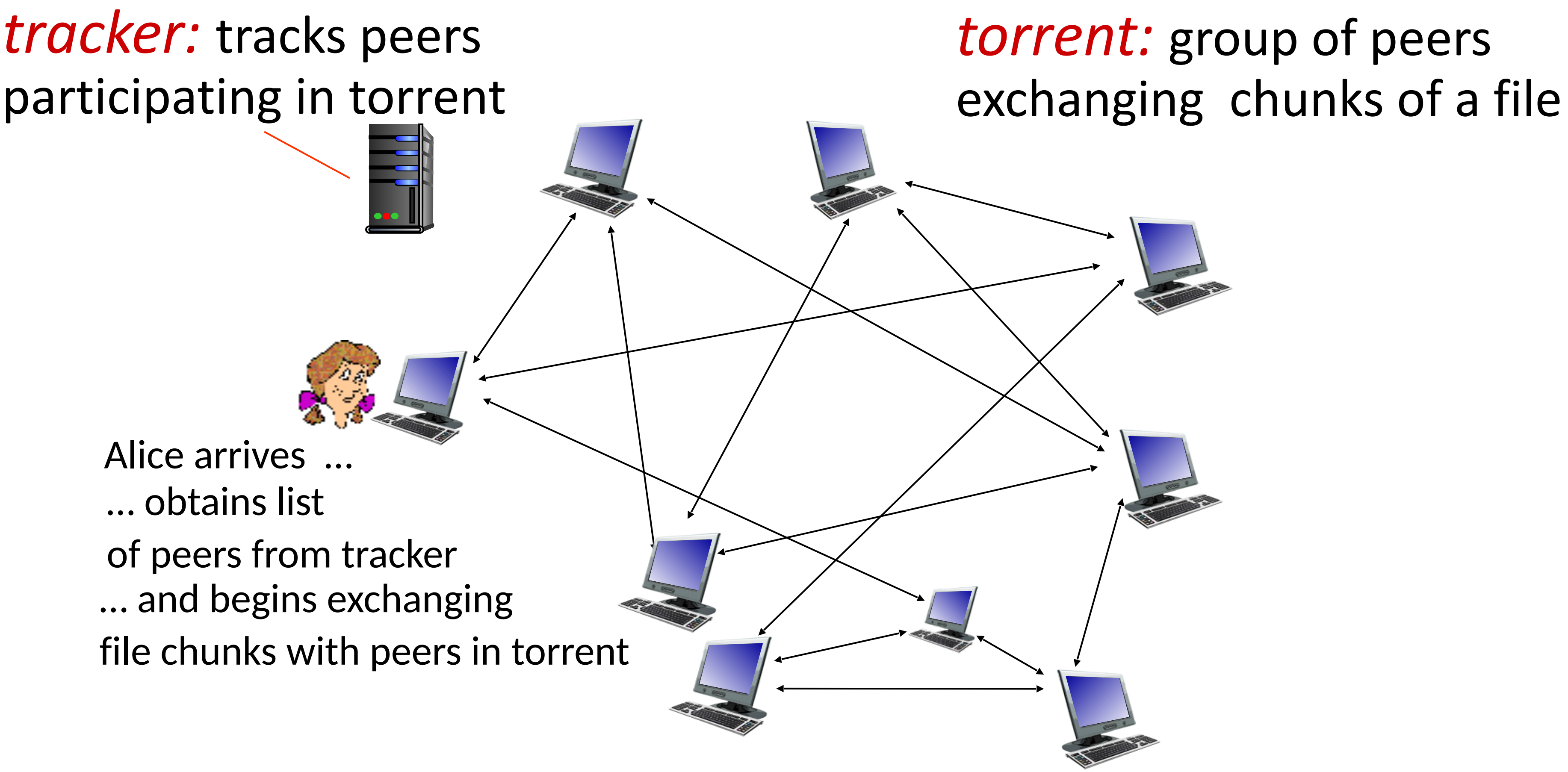

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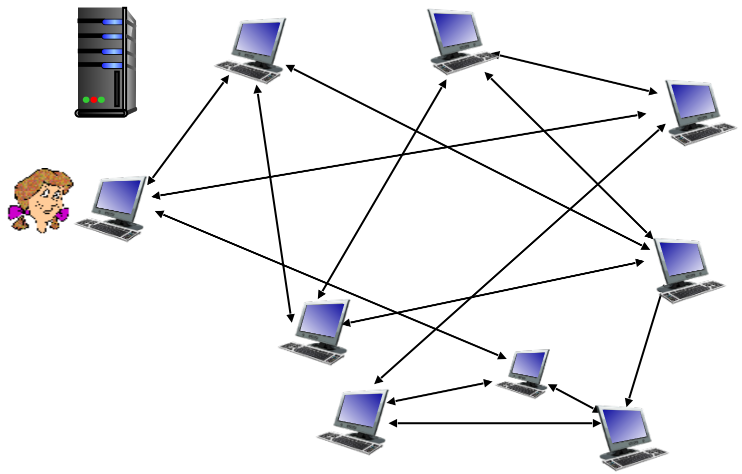


- peer joining torrent:
  - has no chunks, but will accumulate them over time from other peers
  - registers with tracker to get list of peers, connects to subset of peers ("neighbors")
- while downloading, peer uploads chunks to other peers
- peer may change peers with whom it exchanges chunks
- *churn:* peers may come and go
- once peer has entire file, it may (selfishly) leave or (altruistically) remain in torrent

BitTorrent: requesting, sending file chunks

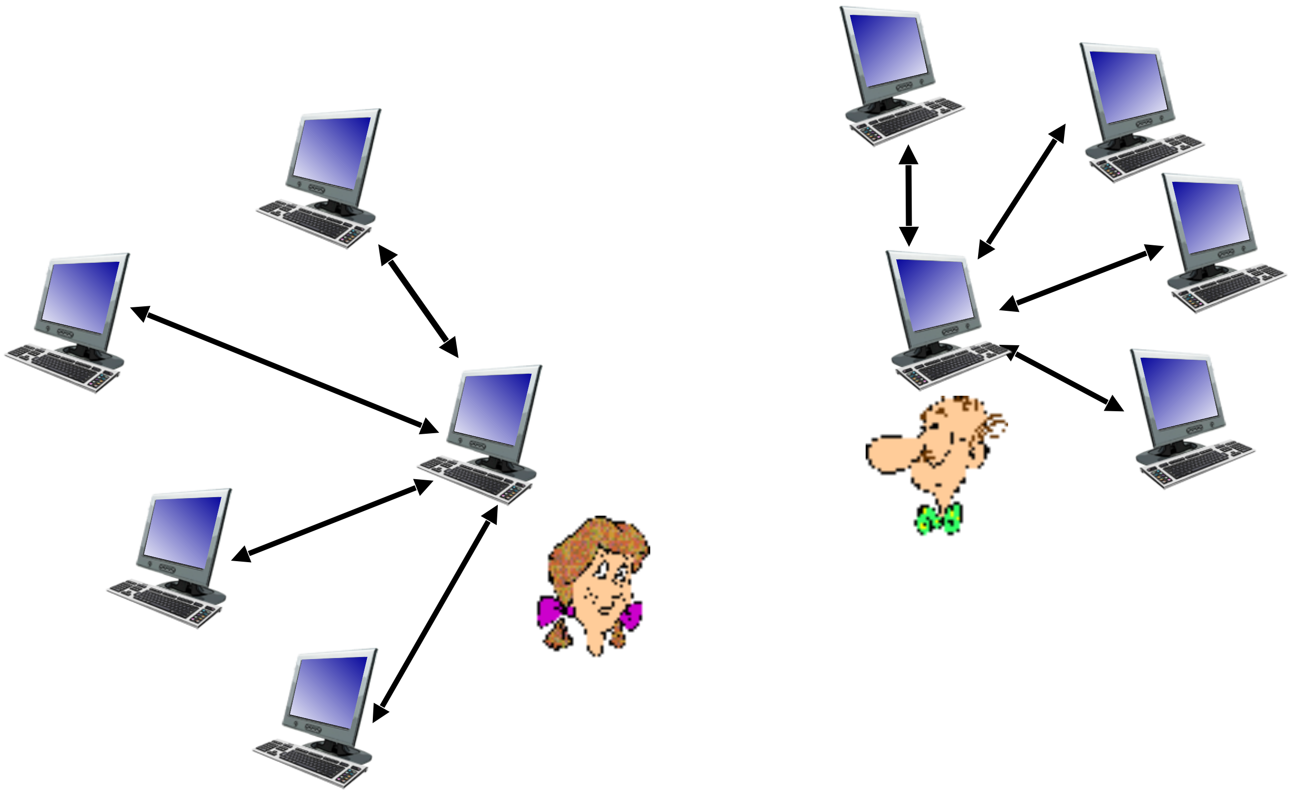
Requesting chunks:

- at any given time, different peers have different subsets of file chunks
- periodically, Alice asks each peer for list of chunks that they have
- Alice requests missing chunks from peers, rarest first

Sending chunks: tit-for-tat

- Alice sends chunks to those four peers currently sending her chunks *at highest rate*
  - other peers are choked by Alice (do not receive chunks from her)
  - re-evaluate top 4 every10 secs
- every 30 secs: randomly select another peer, starts sending chunks
  - "optimistically unchoke" this peer
  - newly chosen peer may join top 4

BitTorrent: tit-for-tat



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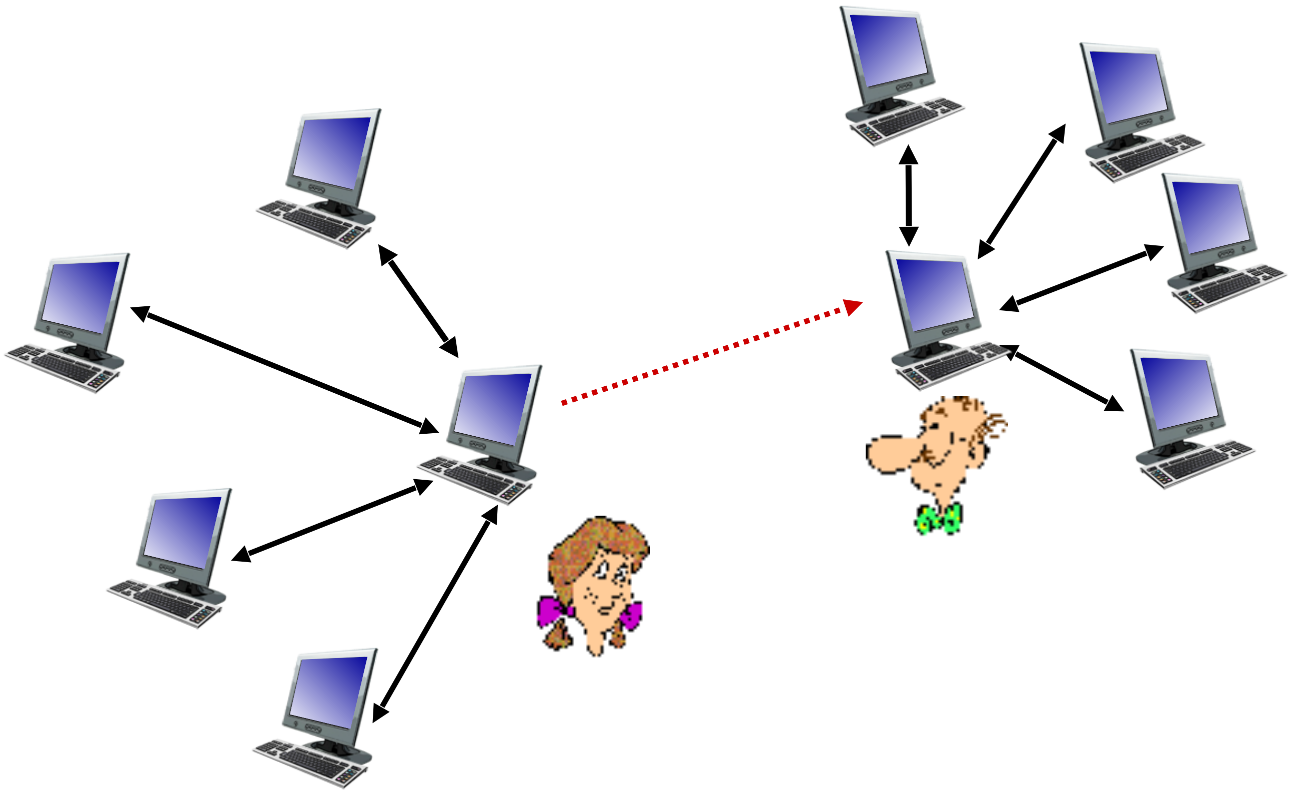

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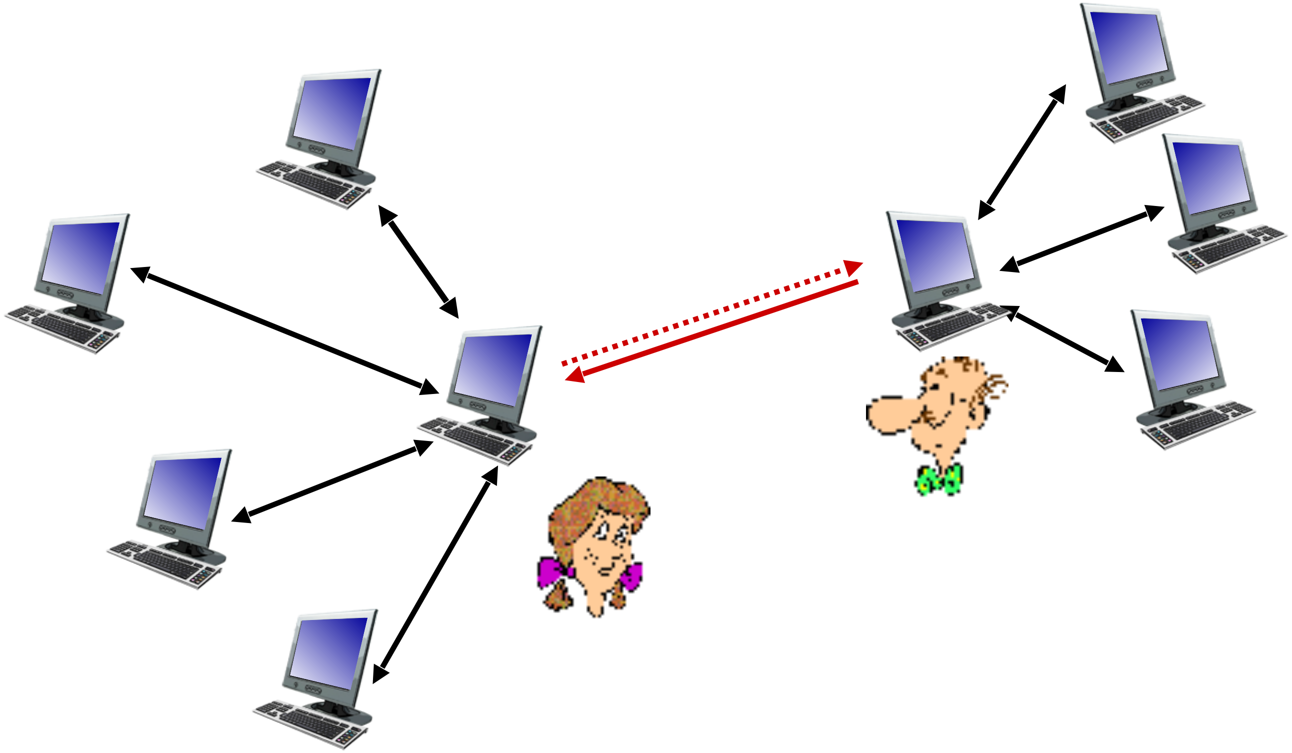

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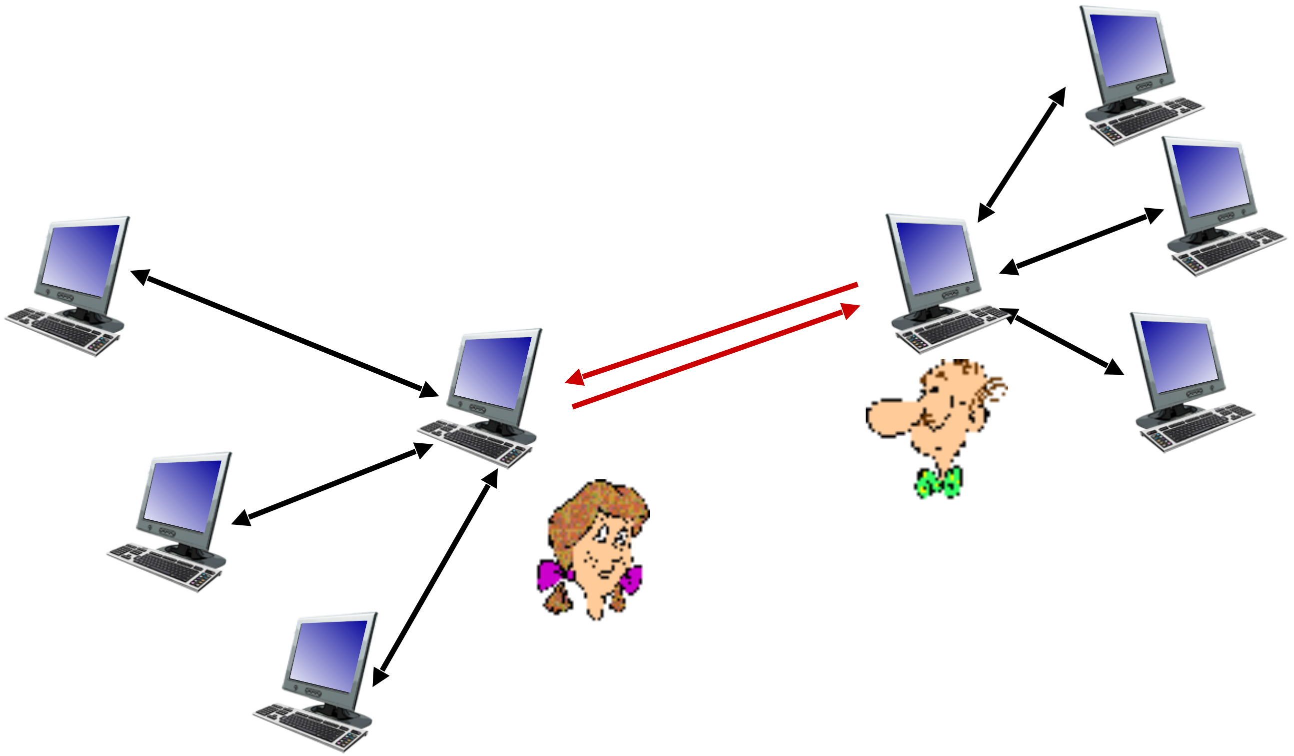
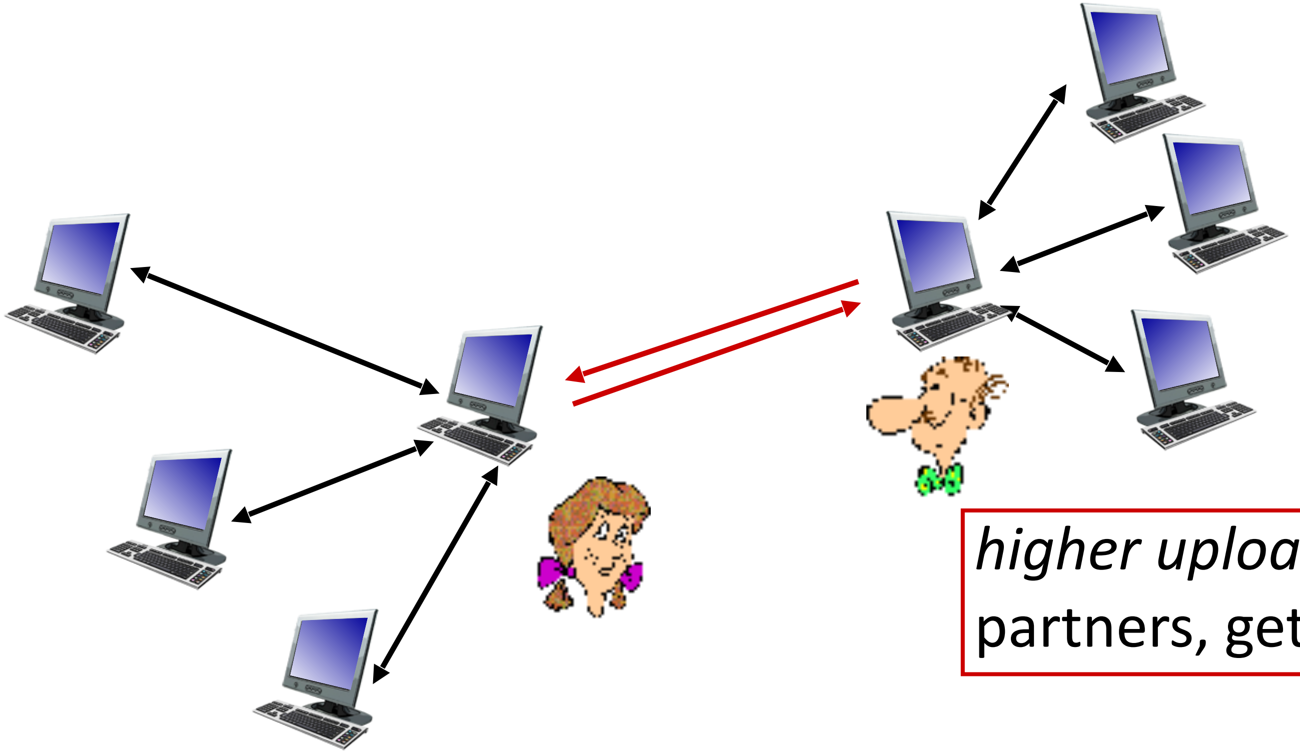


BitTorrent: tit-for-tat

(1) Alice "optimistically unchokes" Bob

(2) Alice becomes one of Bob's top-four providers; Bob reciprocates

(3) Bob becomes one of Alice's top-four providers



higher upload rate: find better trading partners, get file faster !

Chapter 2: outline

- Principles of network applications
- Web and HTTP
- Electronic mail (E-mail)
  - SMTP, POP3, IMAP
- The Domain Name System (DNS)
- P2P applications
- Video streaming and content distribution networks

Video Streaming and CDNs: context

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Multimedia: video

- video: sequence of images displayed at constant rate
  - e.g., 24 images/sec
- digital image: array of pixels
  - each pixel represented by bits
- coding: use redundancy *within* and *between* images to decrease # bits used to encode image
  - spatial (within image)
  - temporal (from one image to next)

spatial coding example: instead of sending *N* values of same color (all purple), send only two values: color value (*purple*) *and number of repeated values* (N)

frame *i*

temporal coding example: instead of sending complete frame at i+1, send only differences from frame i

frame *i+1*

Multimedia: video

- CBR: (constant bit rate): video encoding rate fixed
- VBR: (variable bit rate): video encoding rate changes as amount of spatial, temporal coding changes
- examples:
  - MPEG 1 (CD-ROM) 1.5 Mbps
  - MPEG2 (DVD) 3-6 Mbps
  - MPEG4 (often used in Internet, 64Kbps – 12 Mbps)

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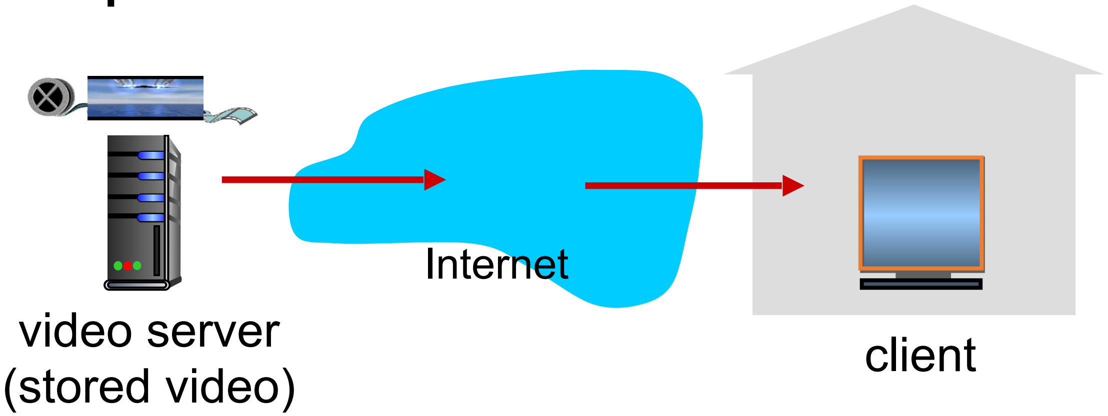
Streaming stored video

simple scenario:



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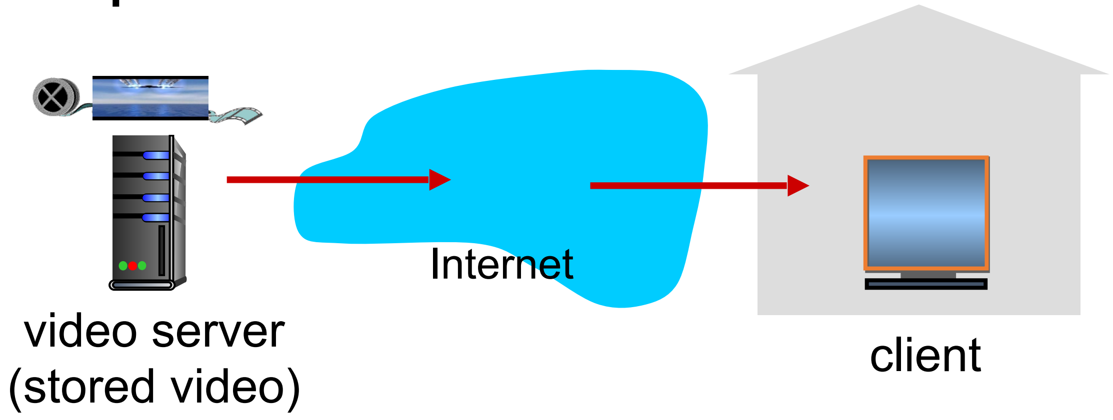

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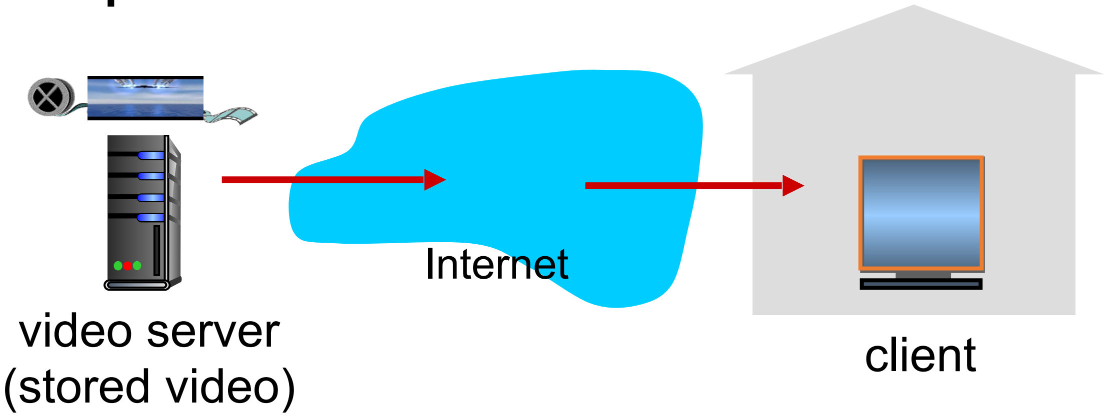
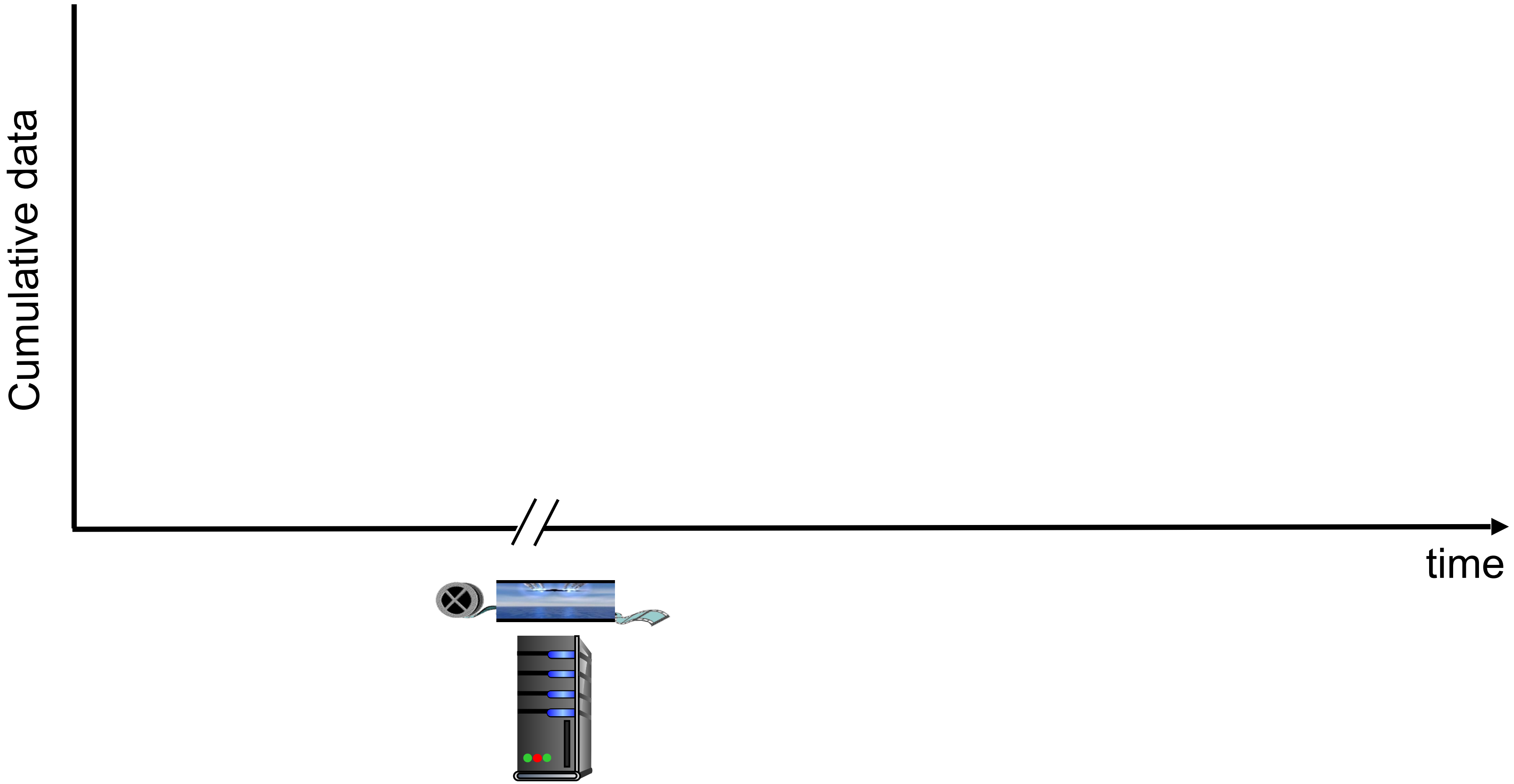


Main challenges:

- server-to-client bandwidth will *vary* over time, with changing network congestion levels (in house, access network, network core, video server)
- packet loss, delay due to congestion will delay playout, or result in poor video quality

Streaming stored video



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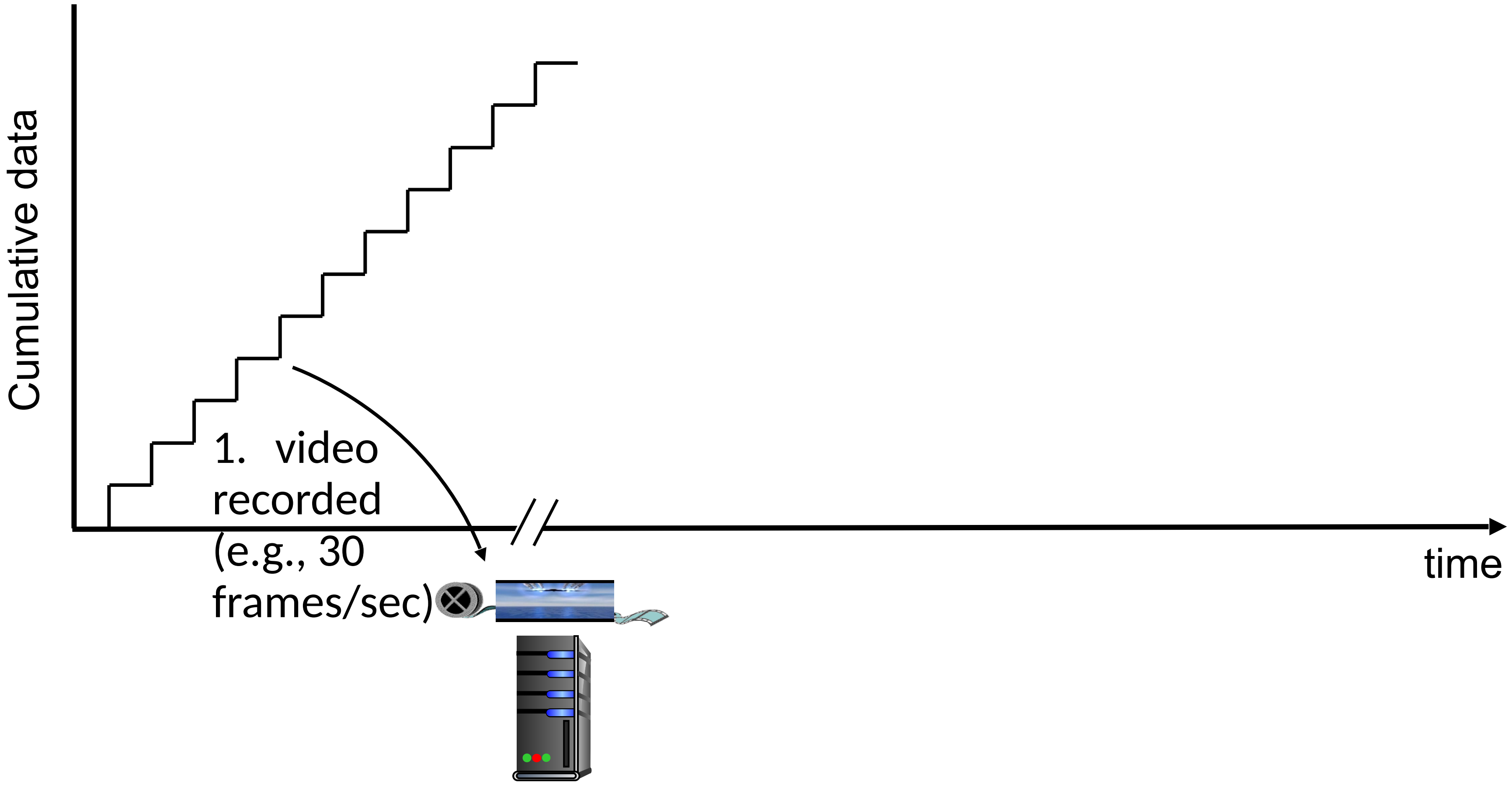

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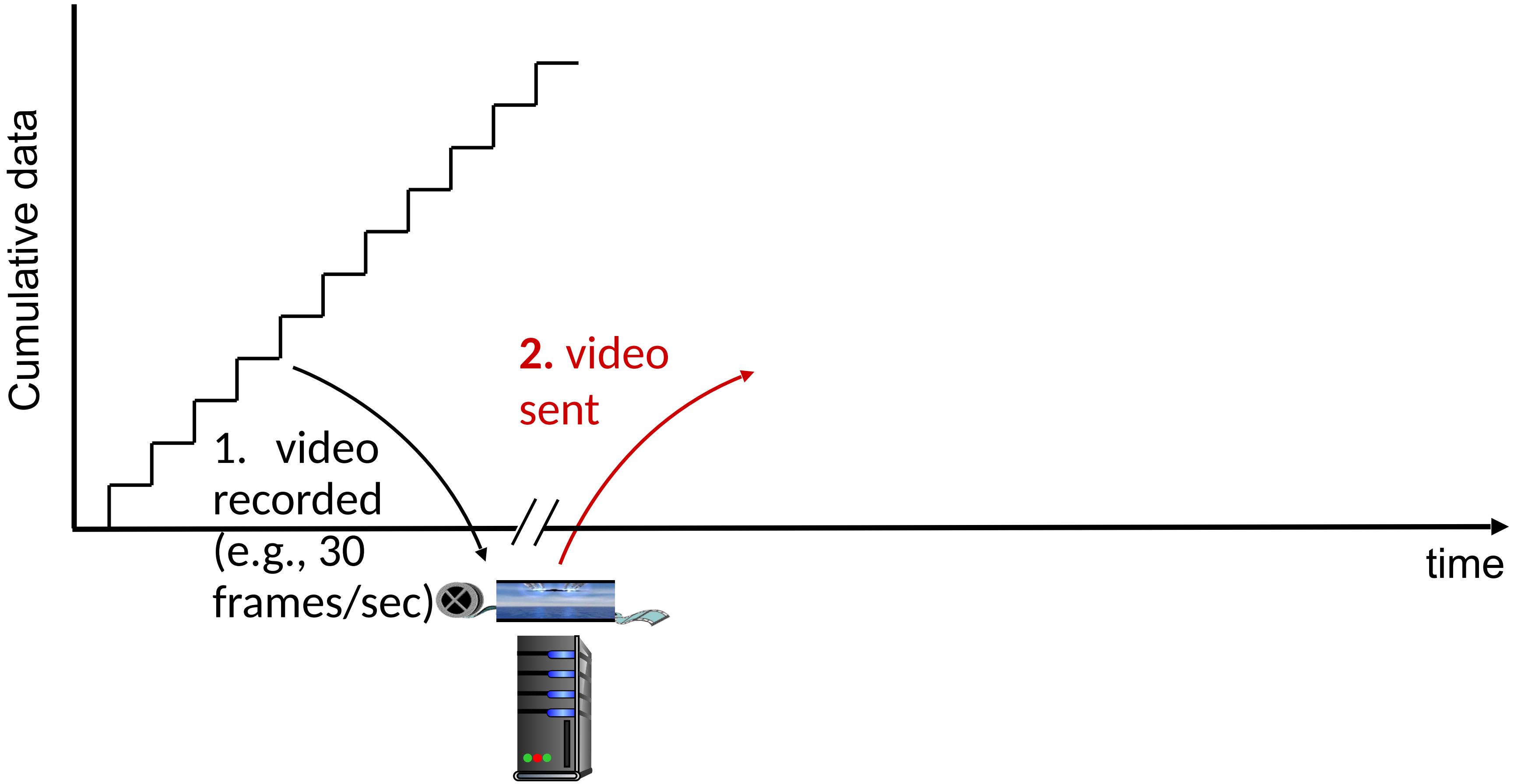

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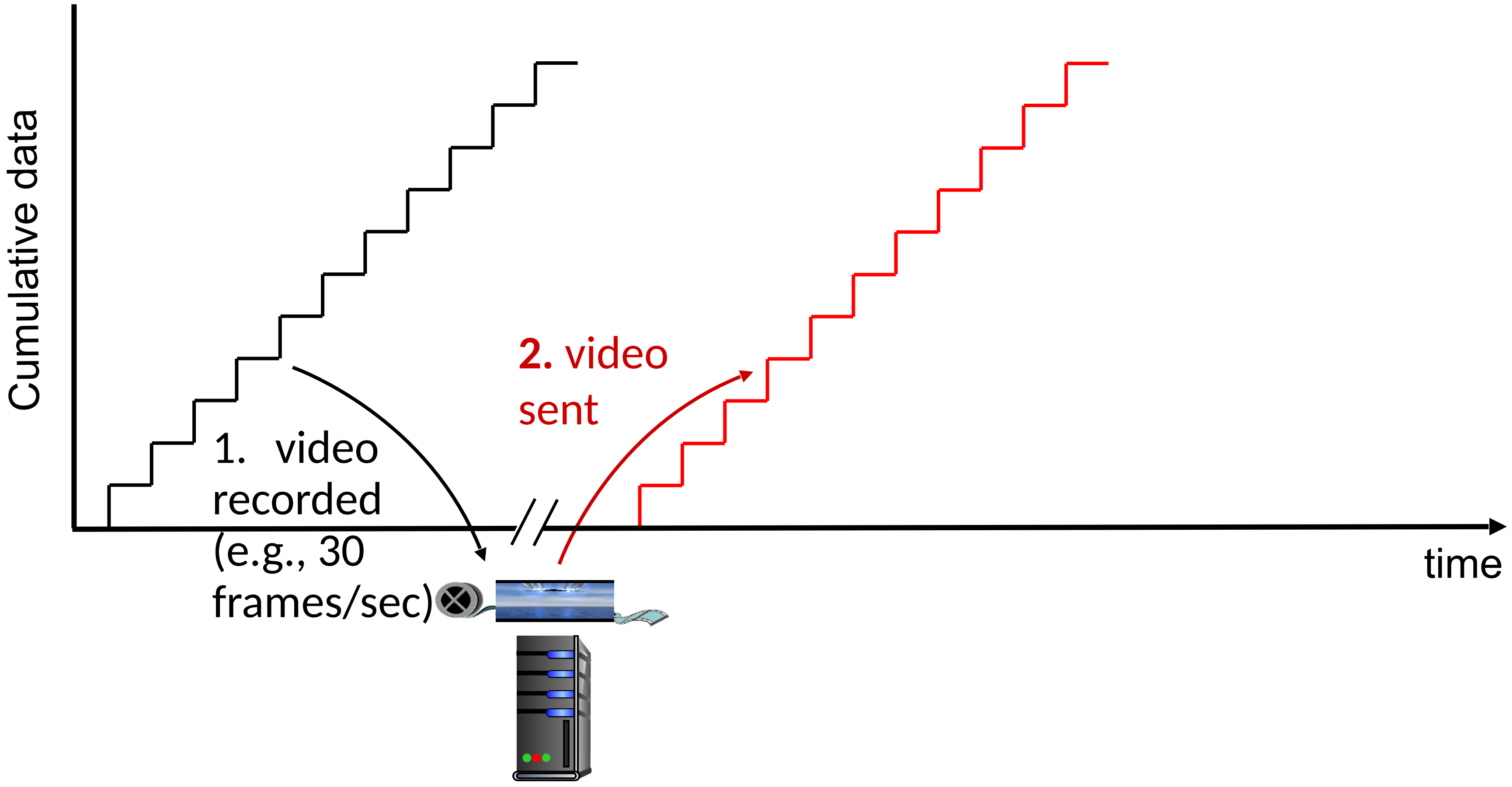

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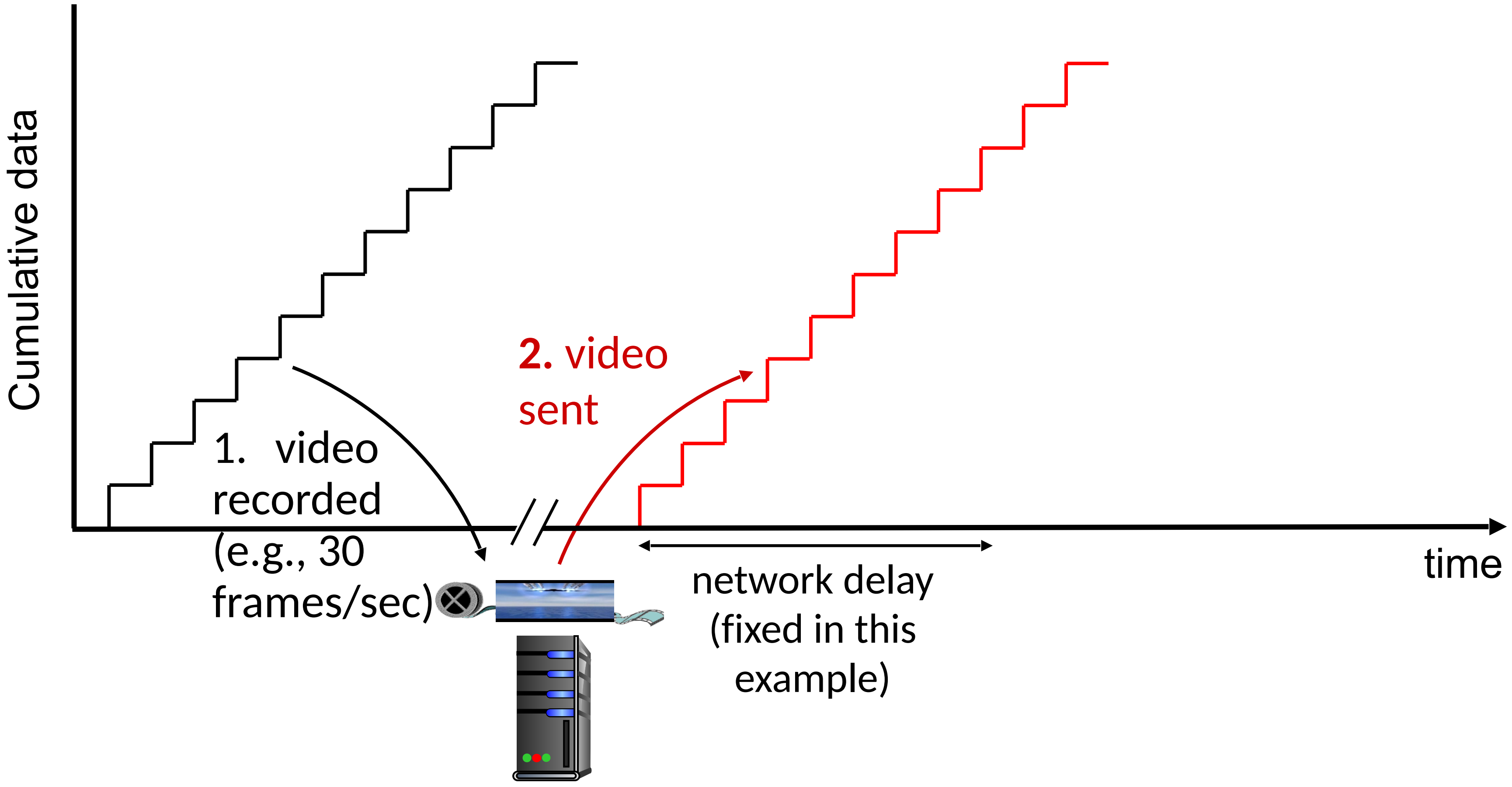

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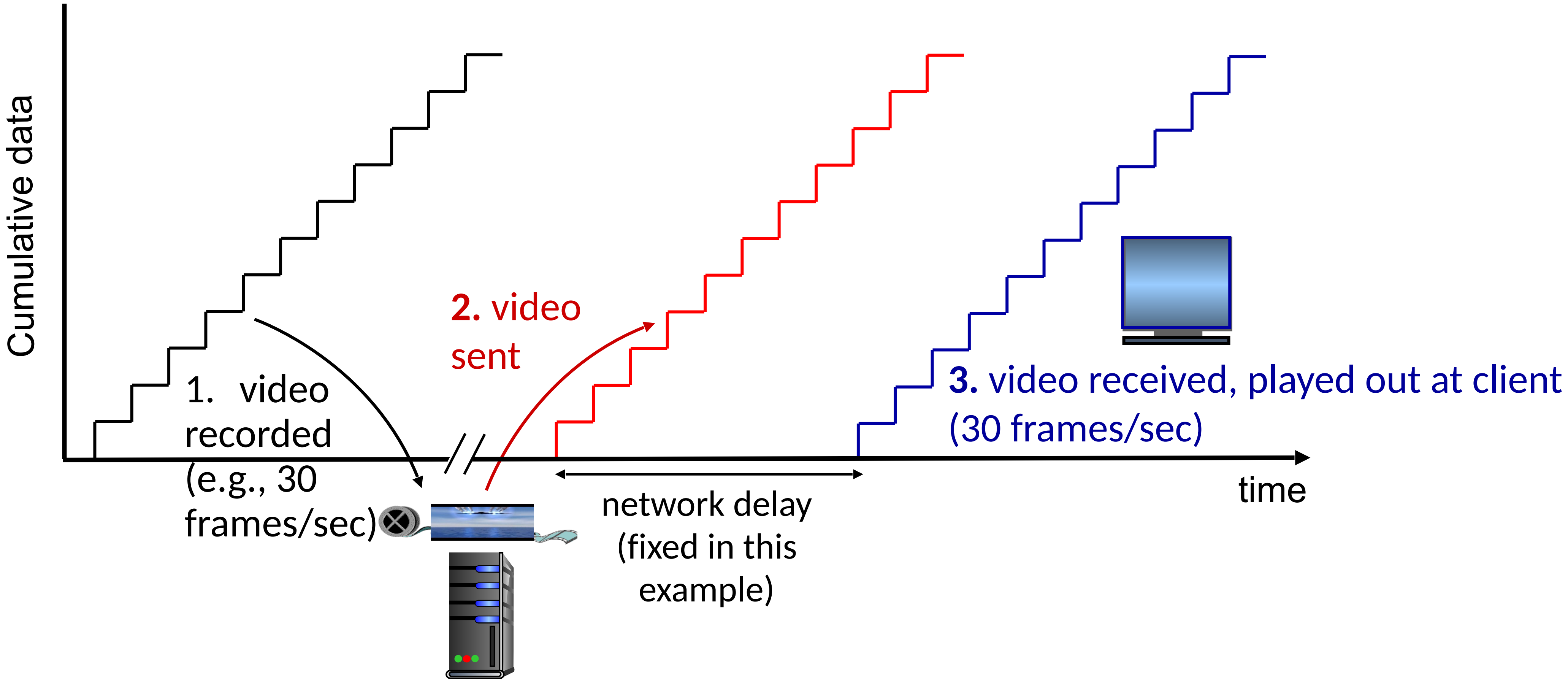

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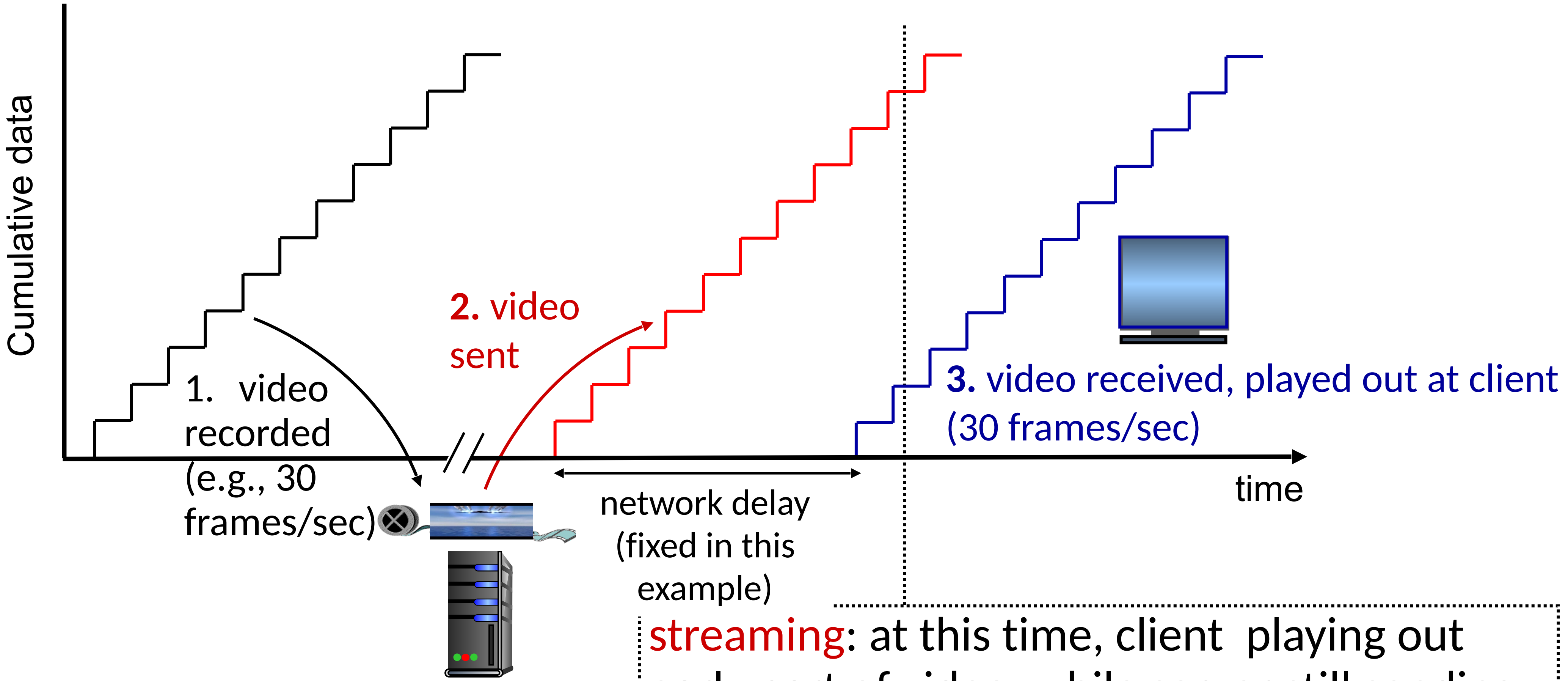
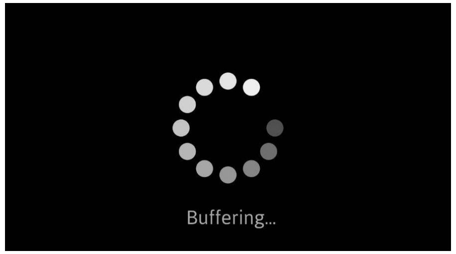


streaming: at this time, client playing out early part of video, while server still sending later part of video

Streaming stored video: challenges



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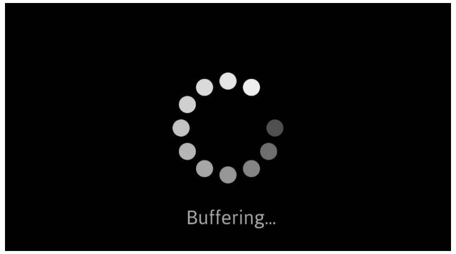
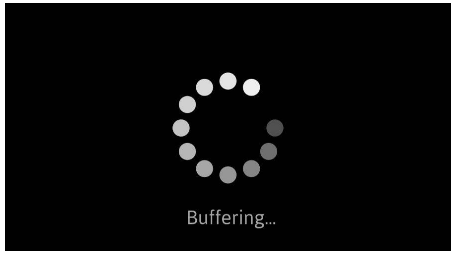


- other challenges:
  - client interactivity: pause, fast-forward, rewind, jump through video
  - video packets may be lost, retransmitted

Streaming stored video: challenges

- continuous playout constraint: during client video playout, playout timing must match original timing
  - … but network delays are variable (jitter), so will need client-side buffer to match continuous playout constraint



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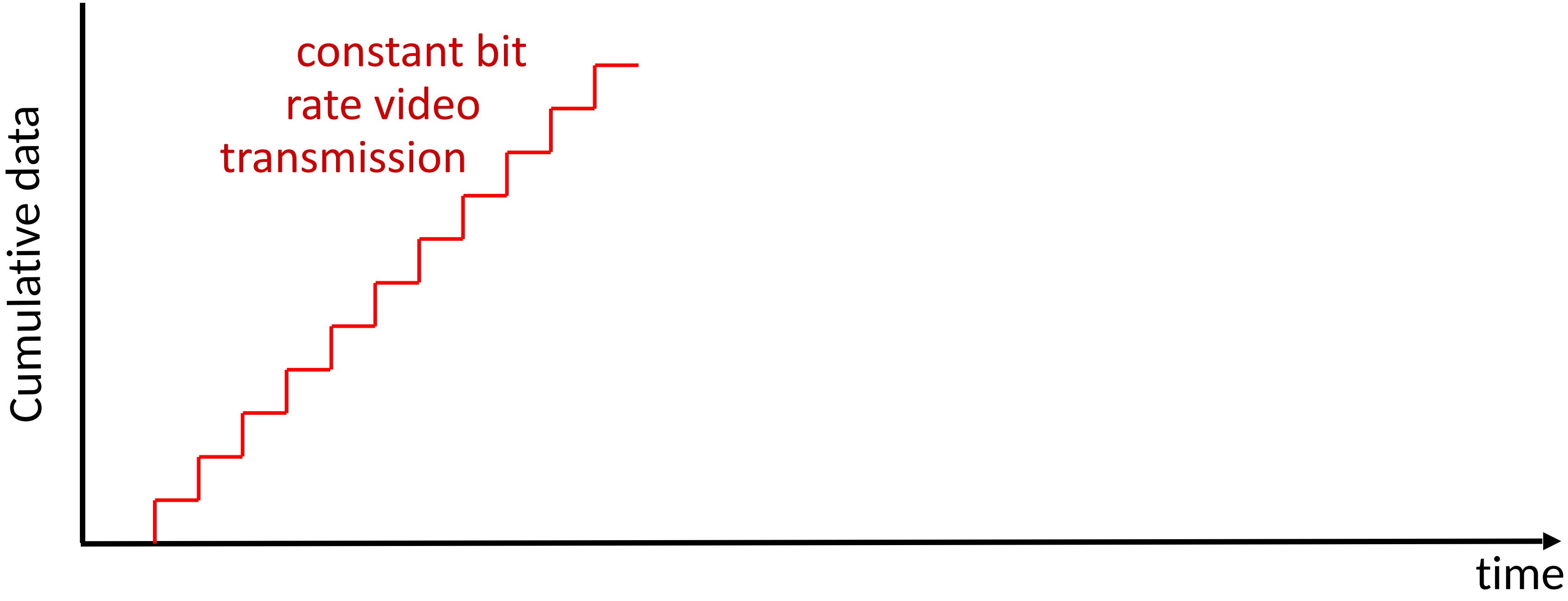

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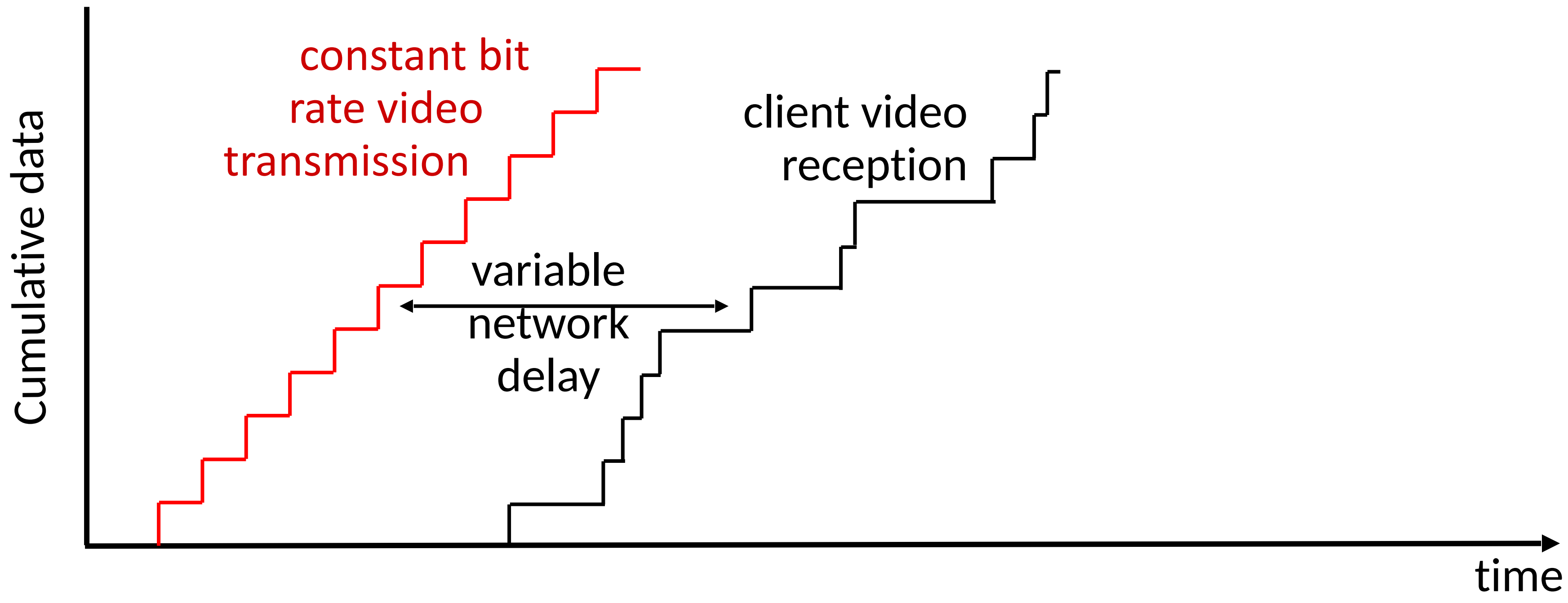

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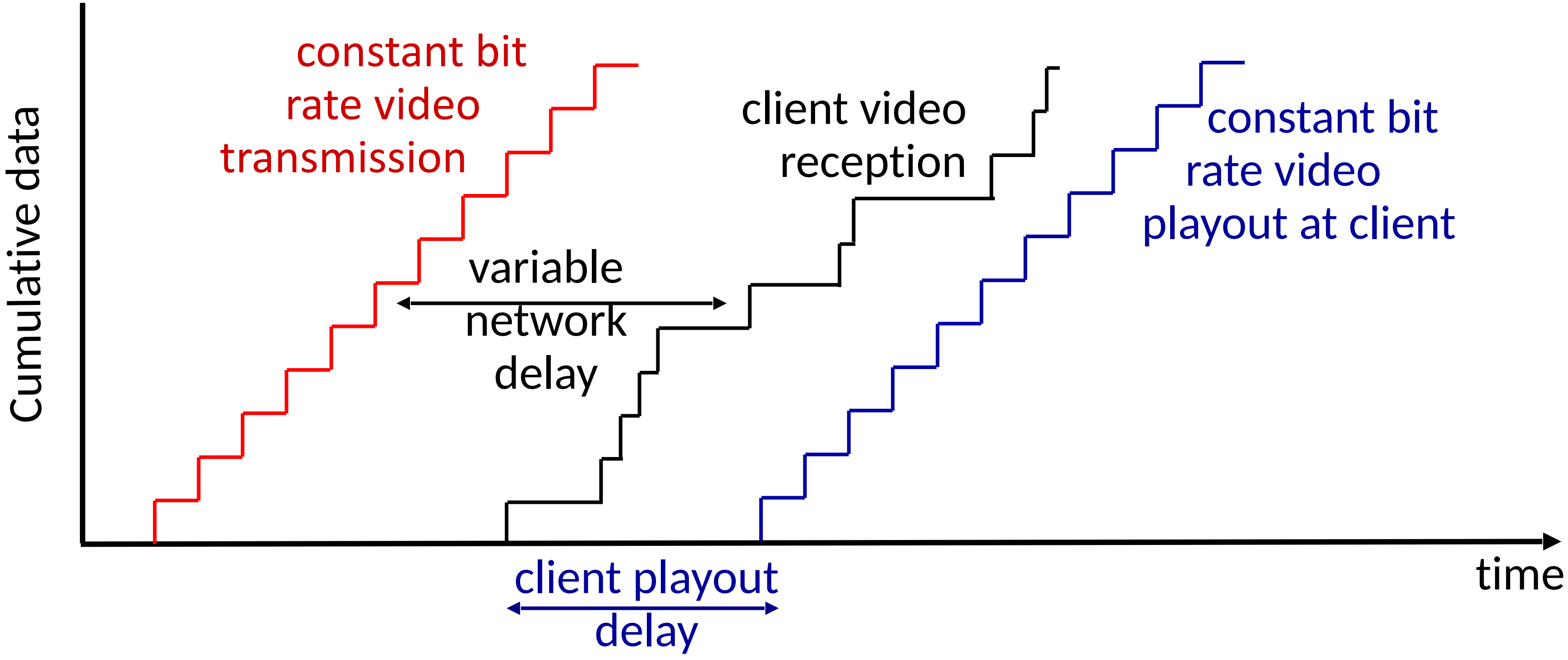

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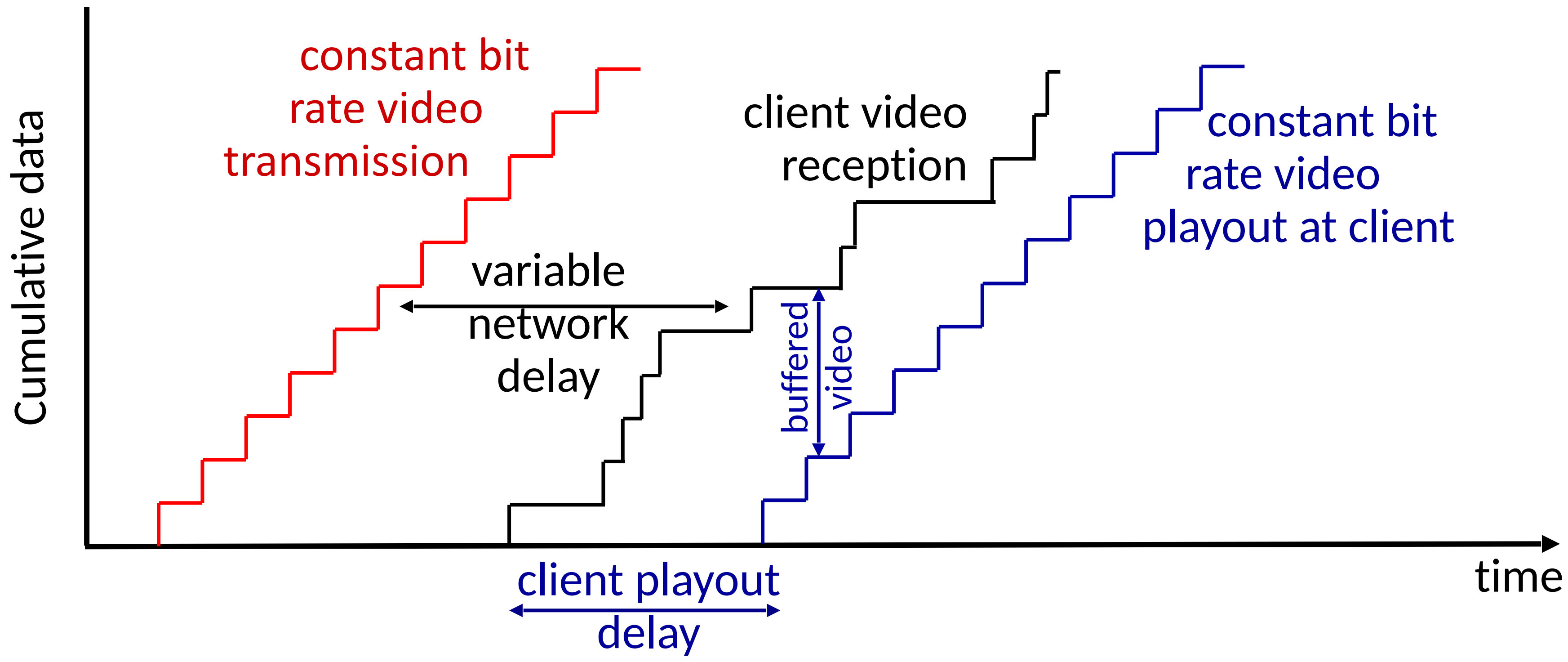
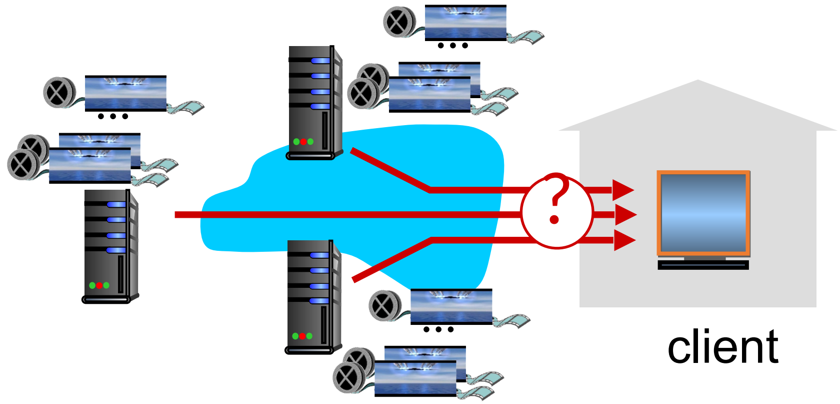


- *client-side buffering and playout delay:* compensate for network-added delay, delay jitter

Streaming multimedia: DASH

*D*ynamic, *A*daptive
*S*treaming over *H*TTP



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server:

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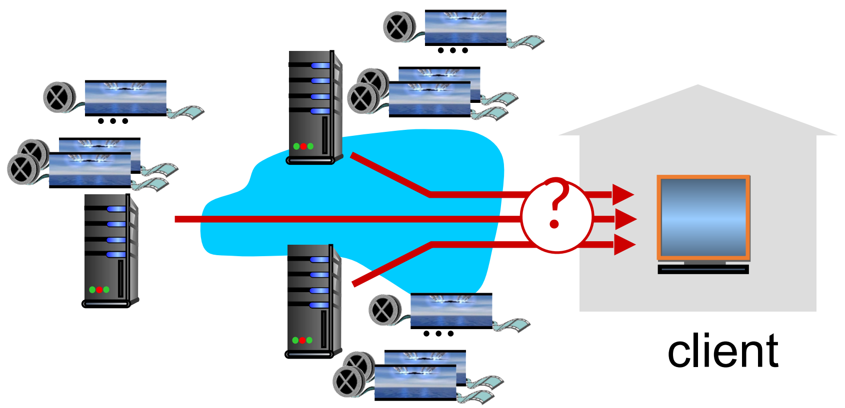

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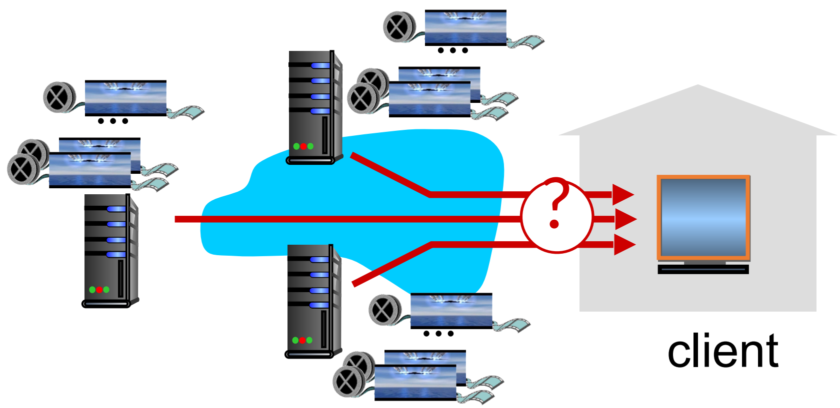

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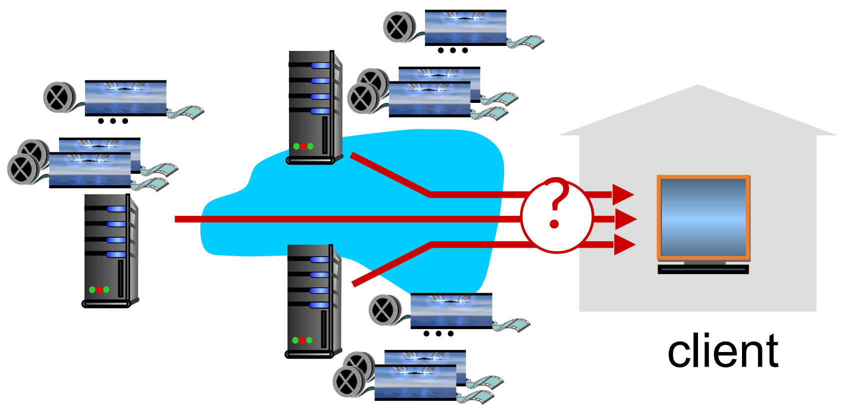

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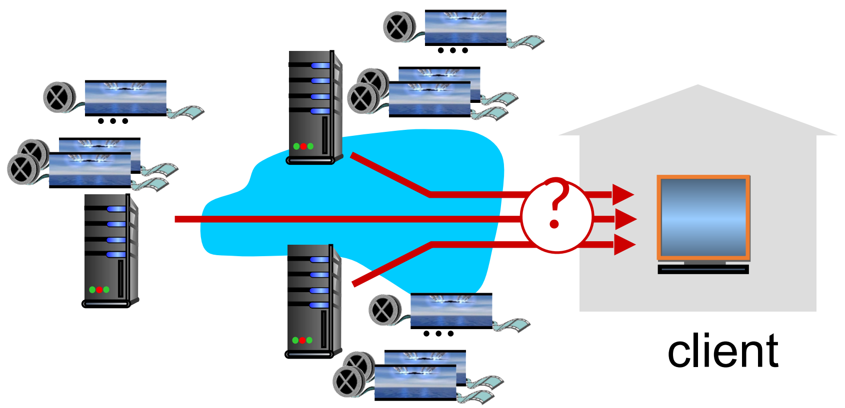

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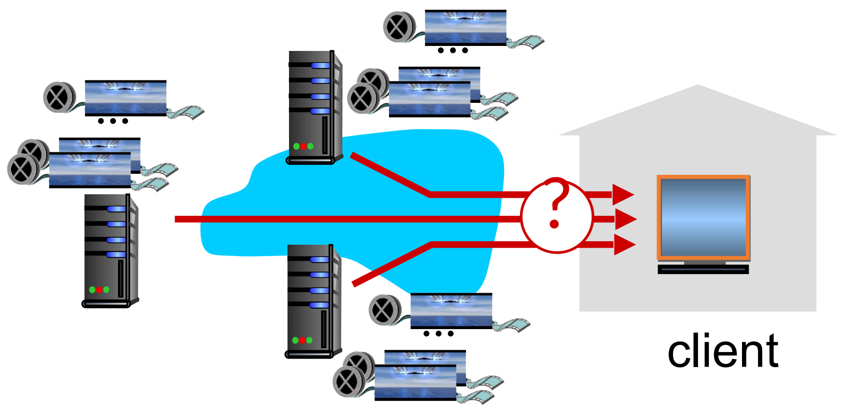

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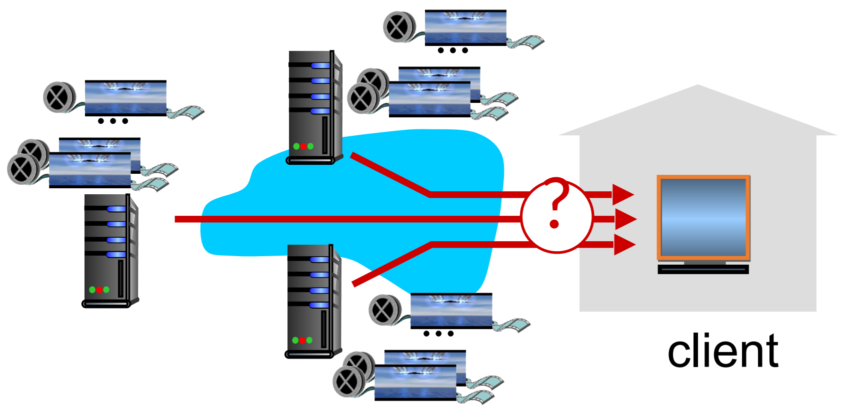

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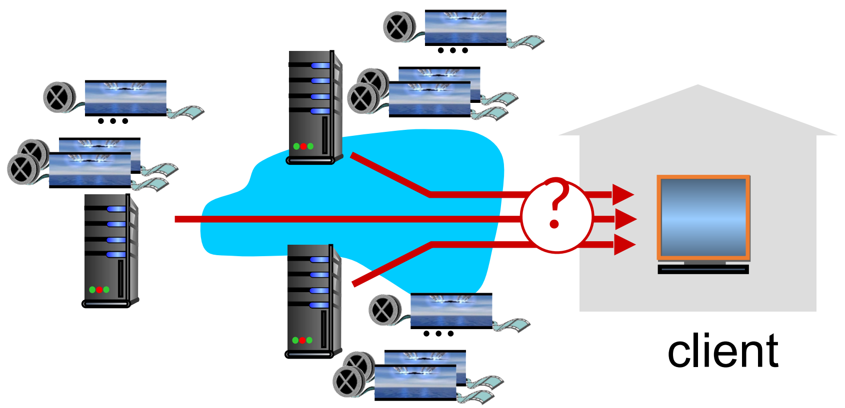

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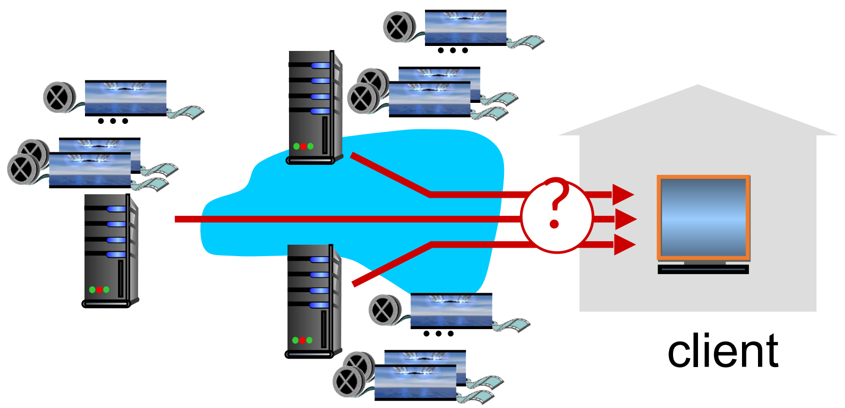
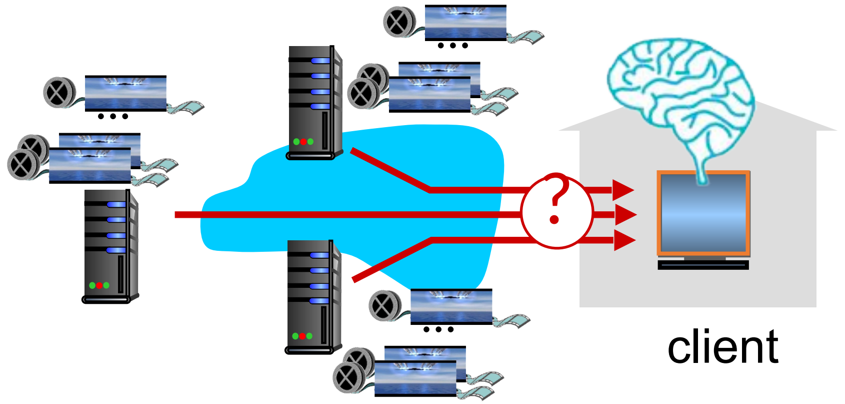


client:

- periodically estimates server-to-client bandwidth
- consulting manifest, requests one chunk at a time
  - chooses maximum coding rate sustainable given current bandwidth
  - can choose different coding rates at different points in time (depending on available bandwidth at time), and from different servers

Streaming multimedia: DASH

- *"intelligence"* at client: client determines



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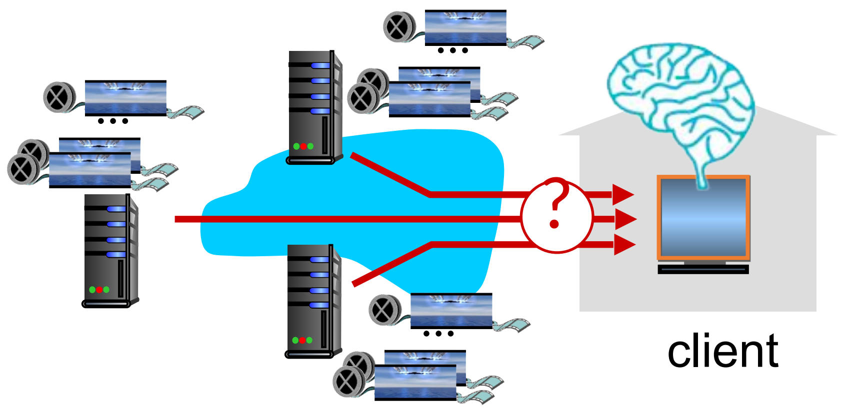

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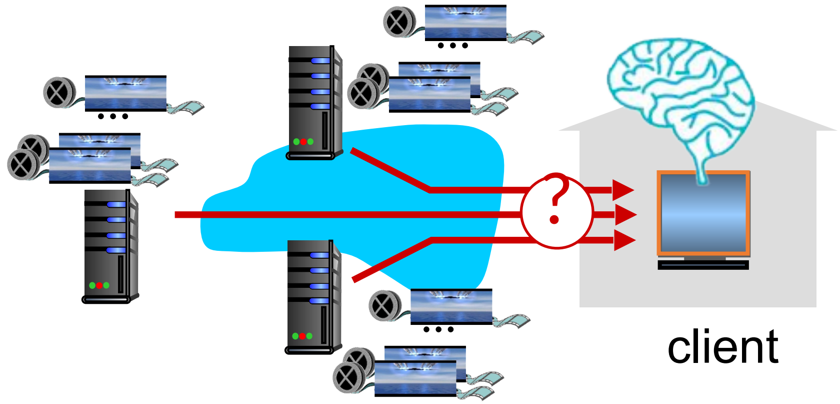

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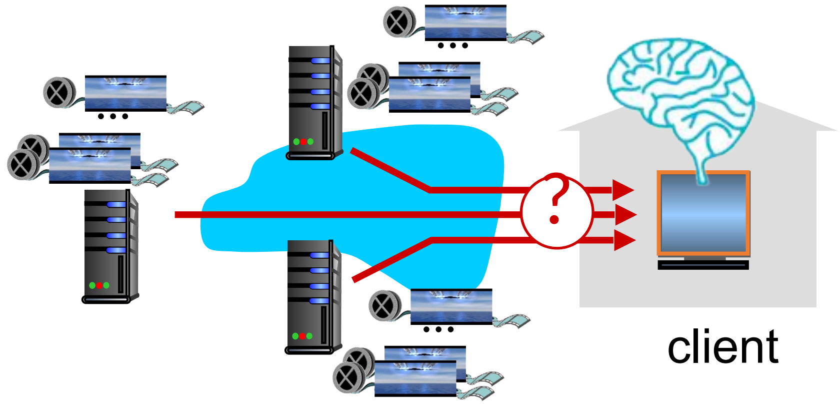

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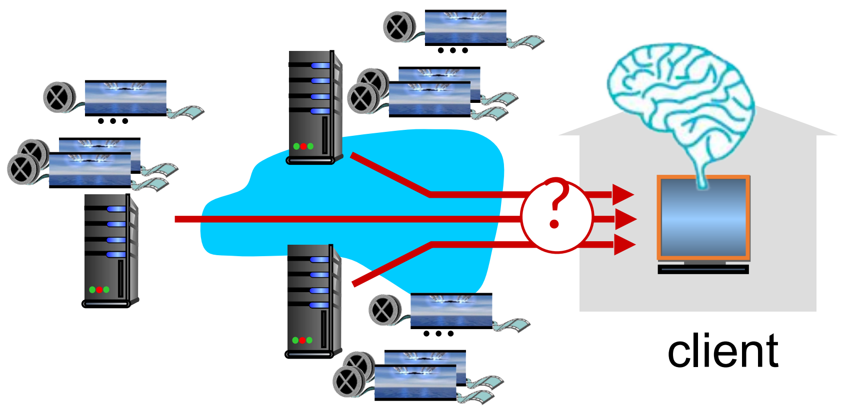

Streaming video = encoding + DASH + playout buffering

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….quite simply: this solution *doesn’t scale*

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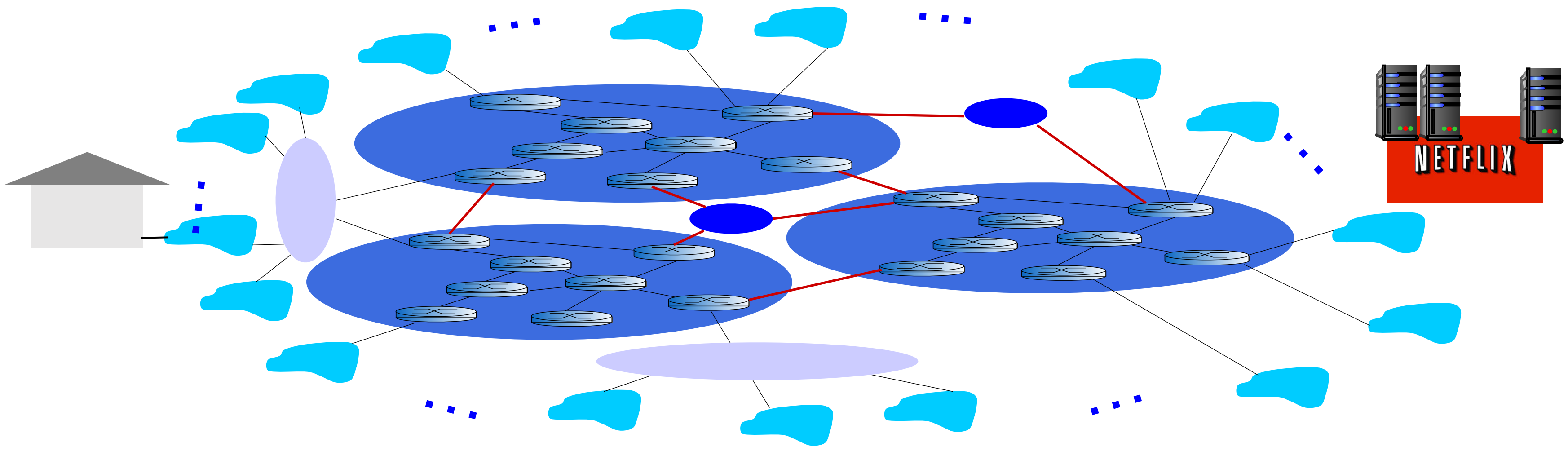
- *bring home:* smaller number (10's) of larger clusters in POPs near access nets
  - used by Limelight

Content distribution networks (CDNs)

- CDN: stores copies of content (e.g. MADMEN) at CDN nodes



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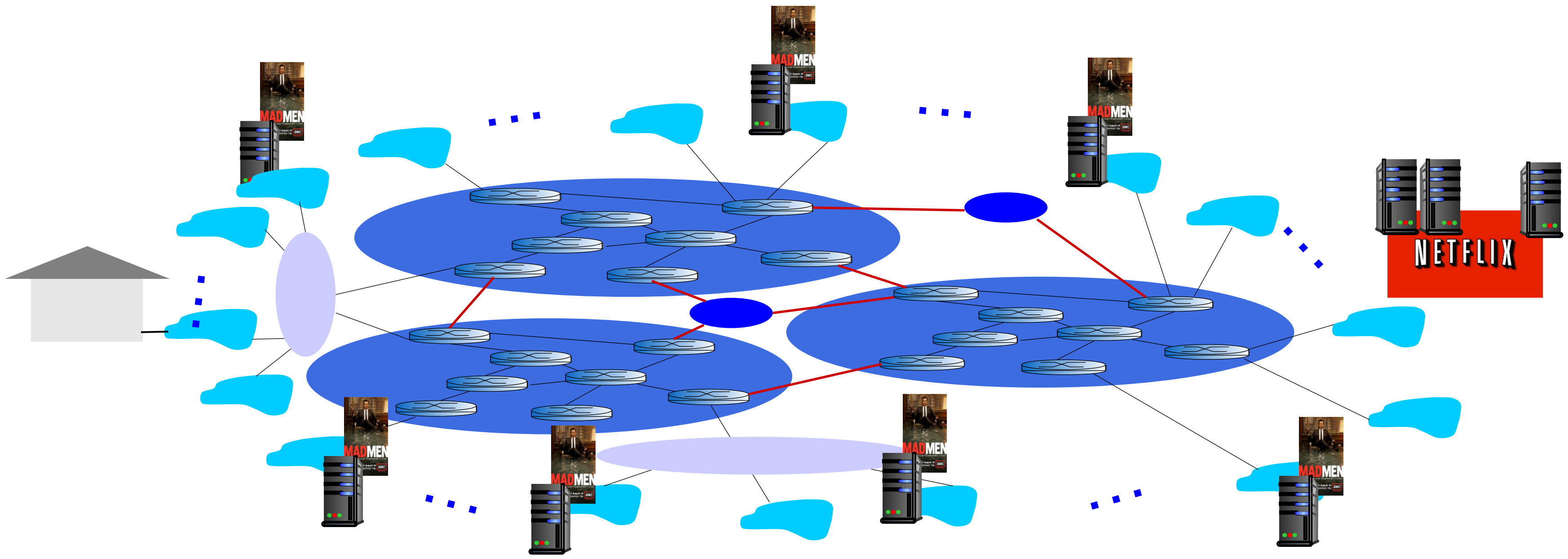

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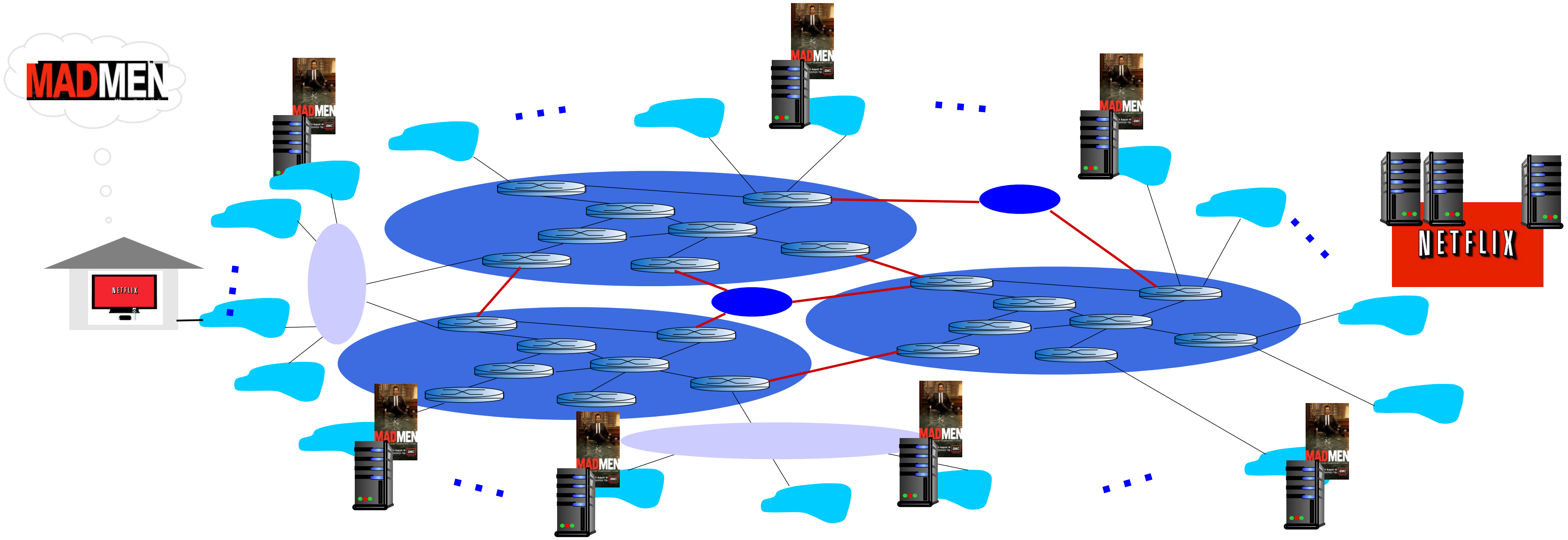

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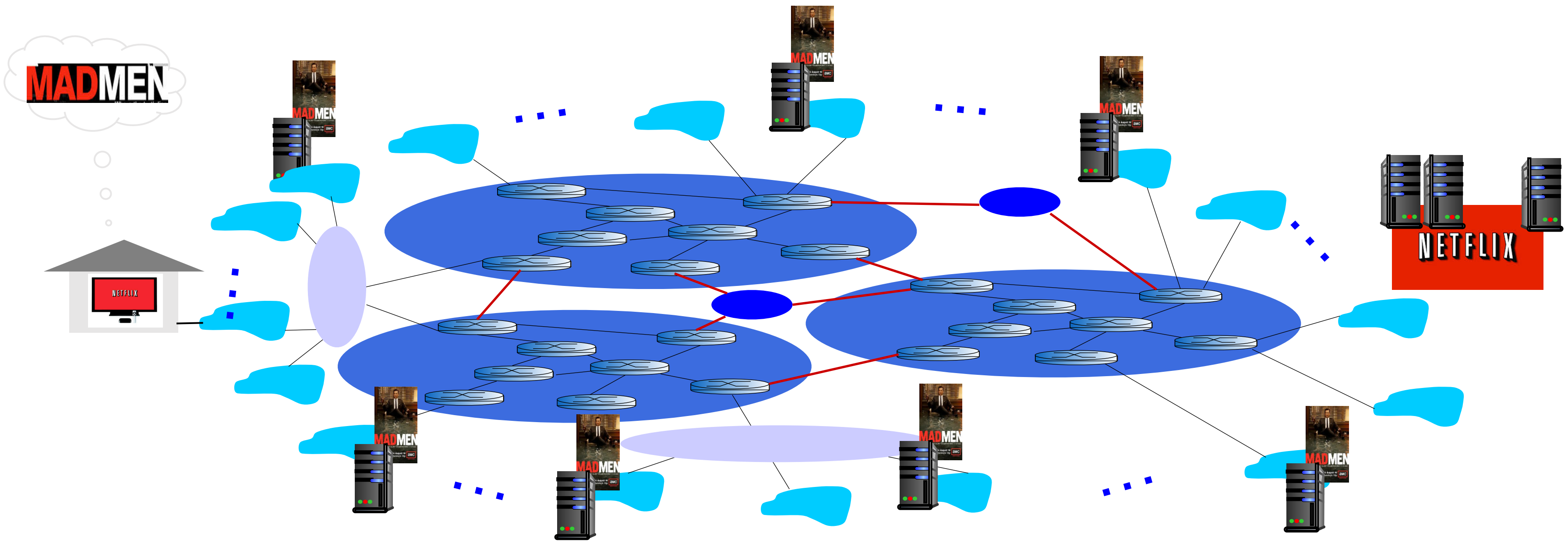

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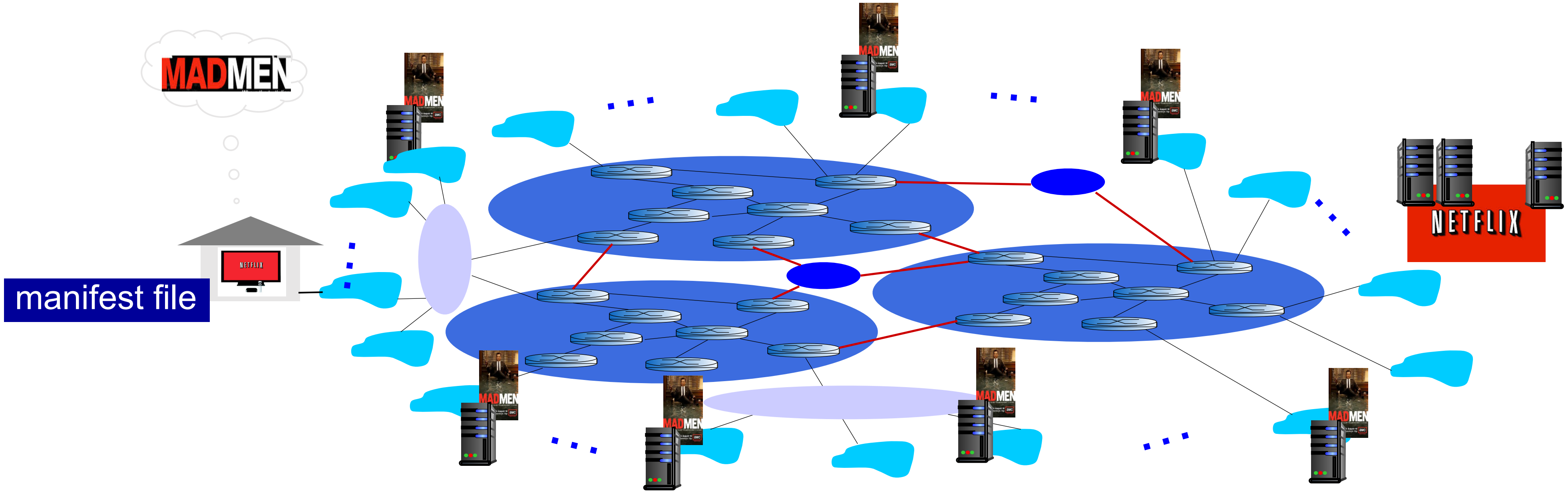

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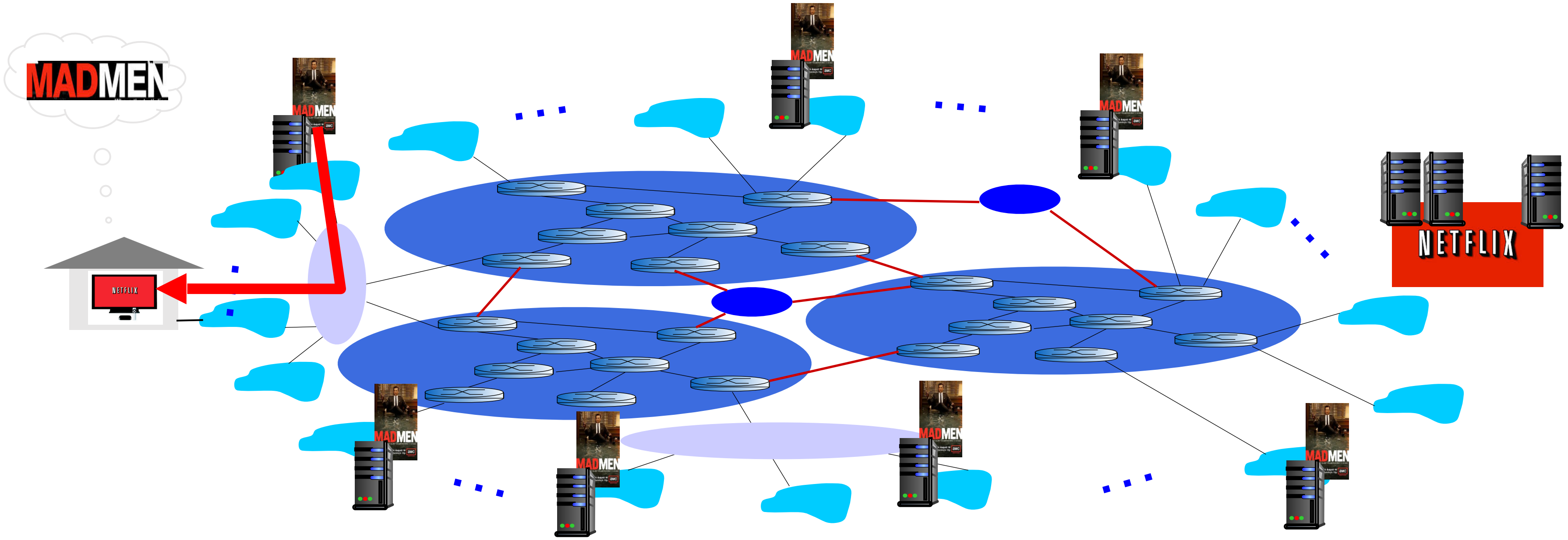

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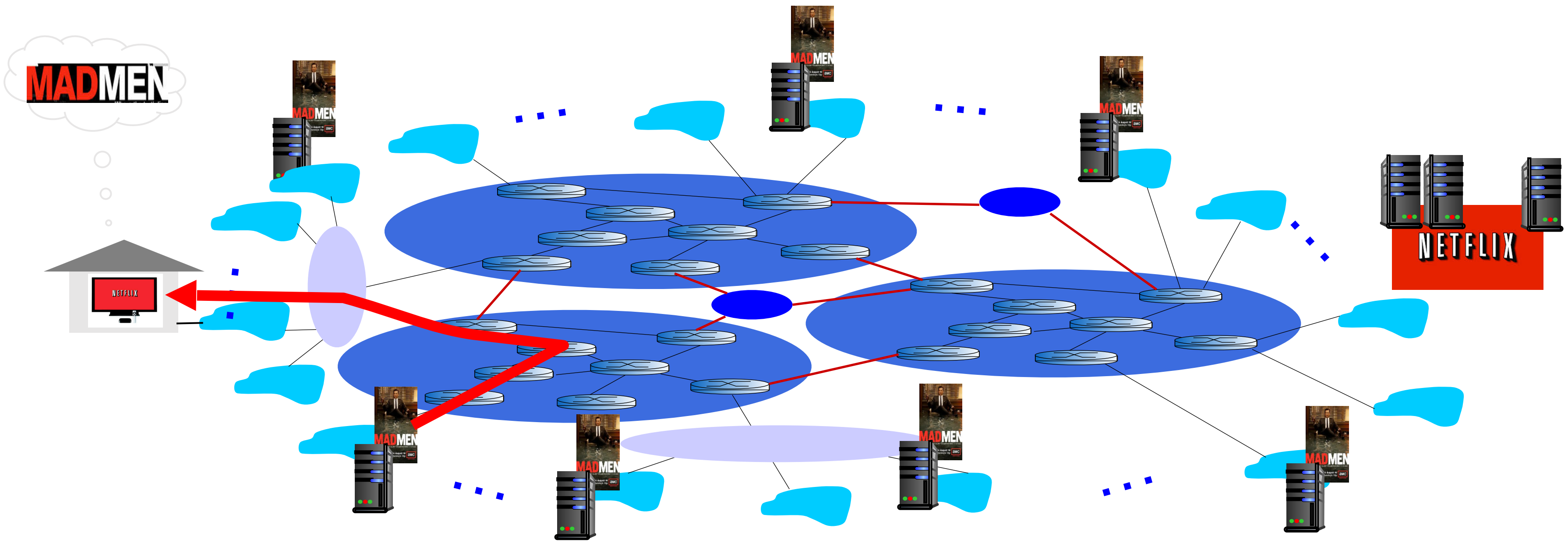
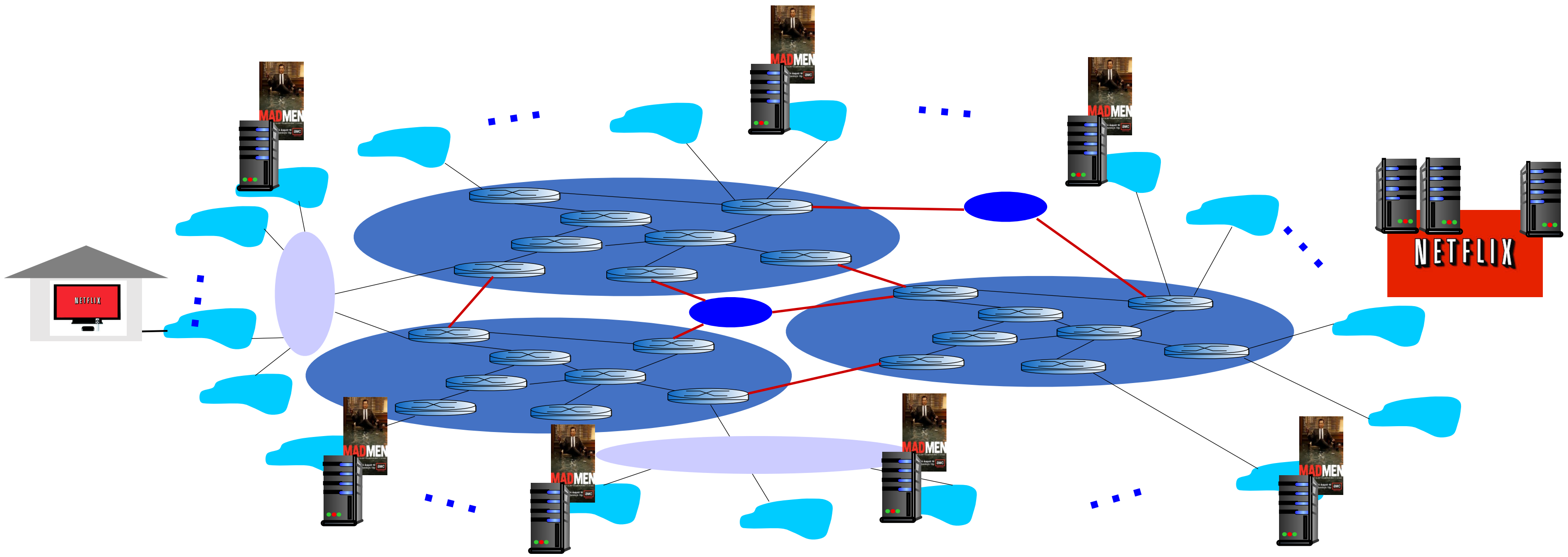
  - may choose different rate or copy if network path congested



Content distribution networks (CDNs)

OTT: "over the top"



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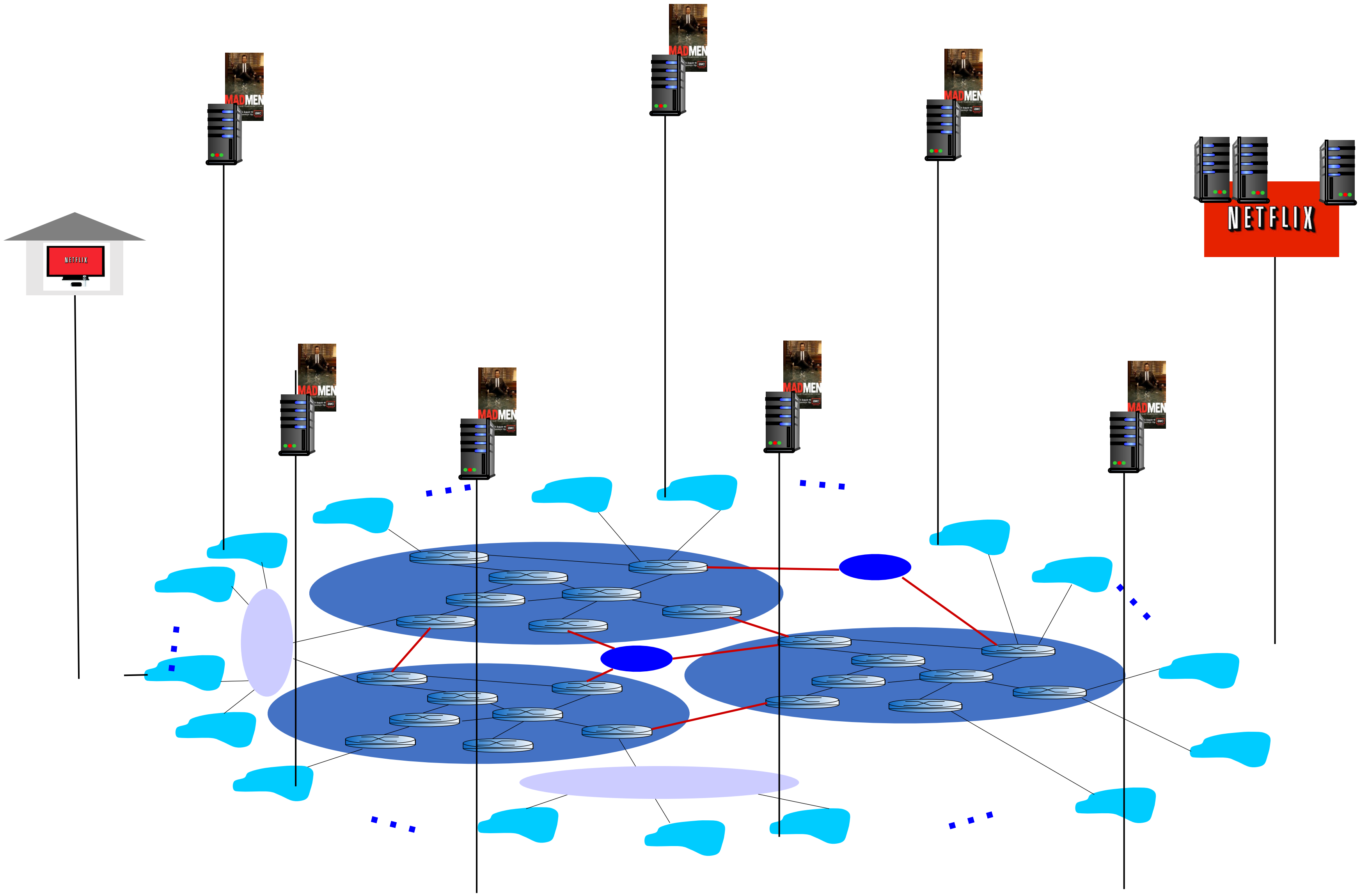

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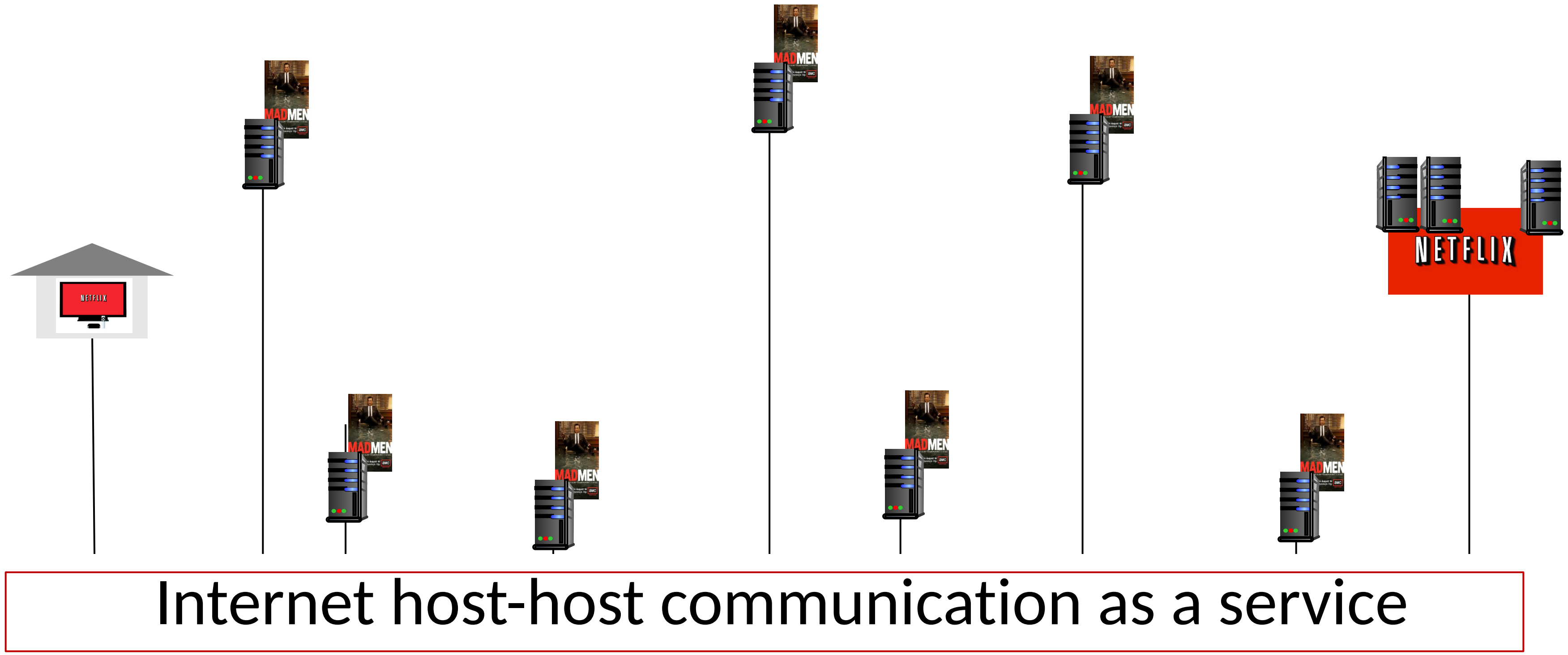

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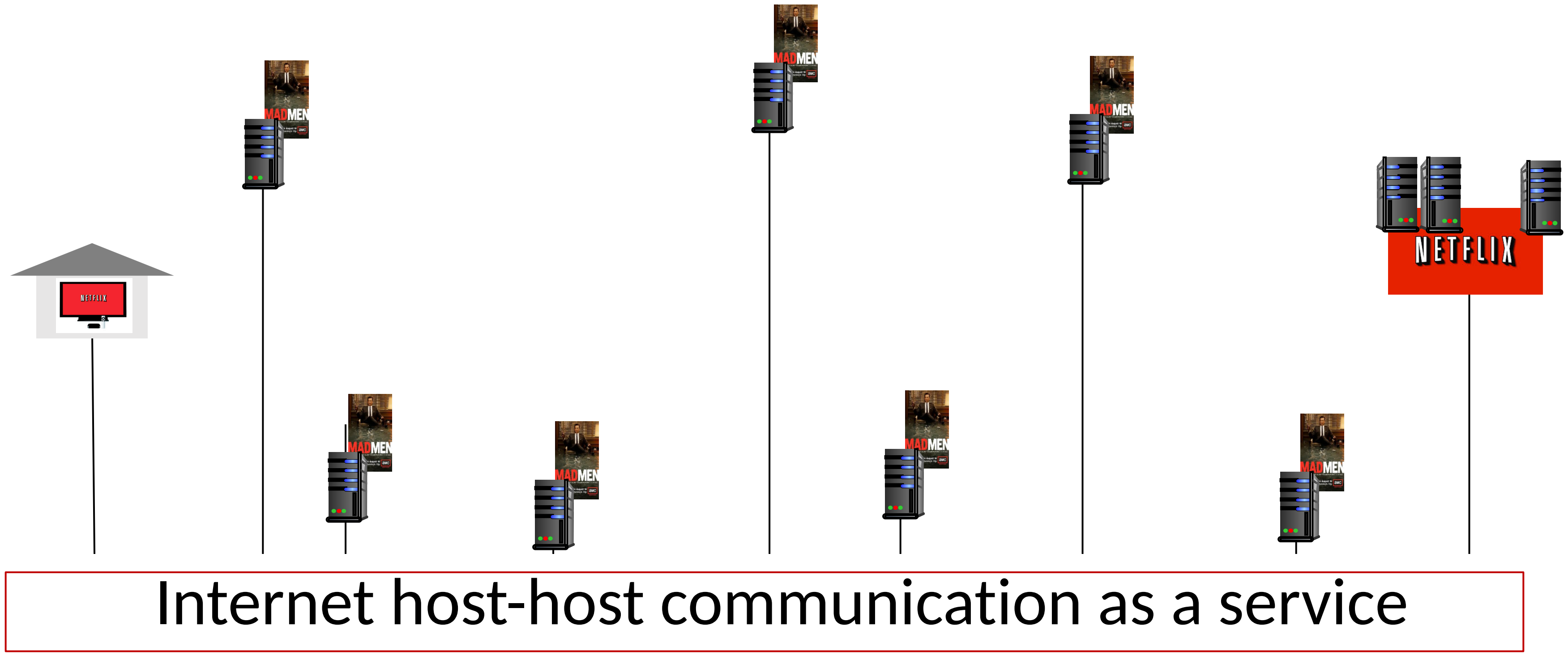


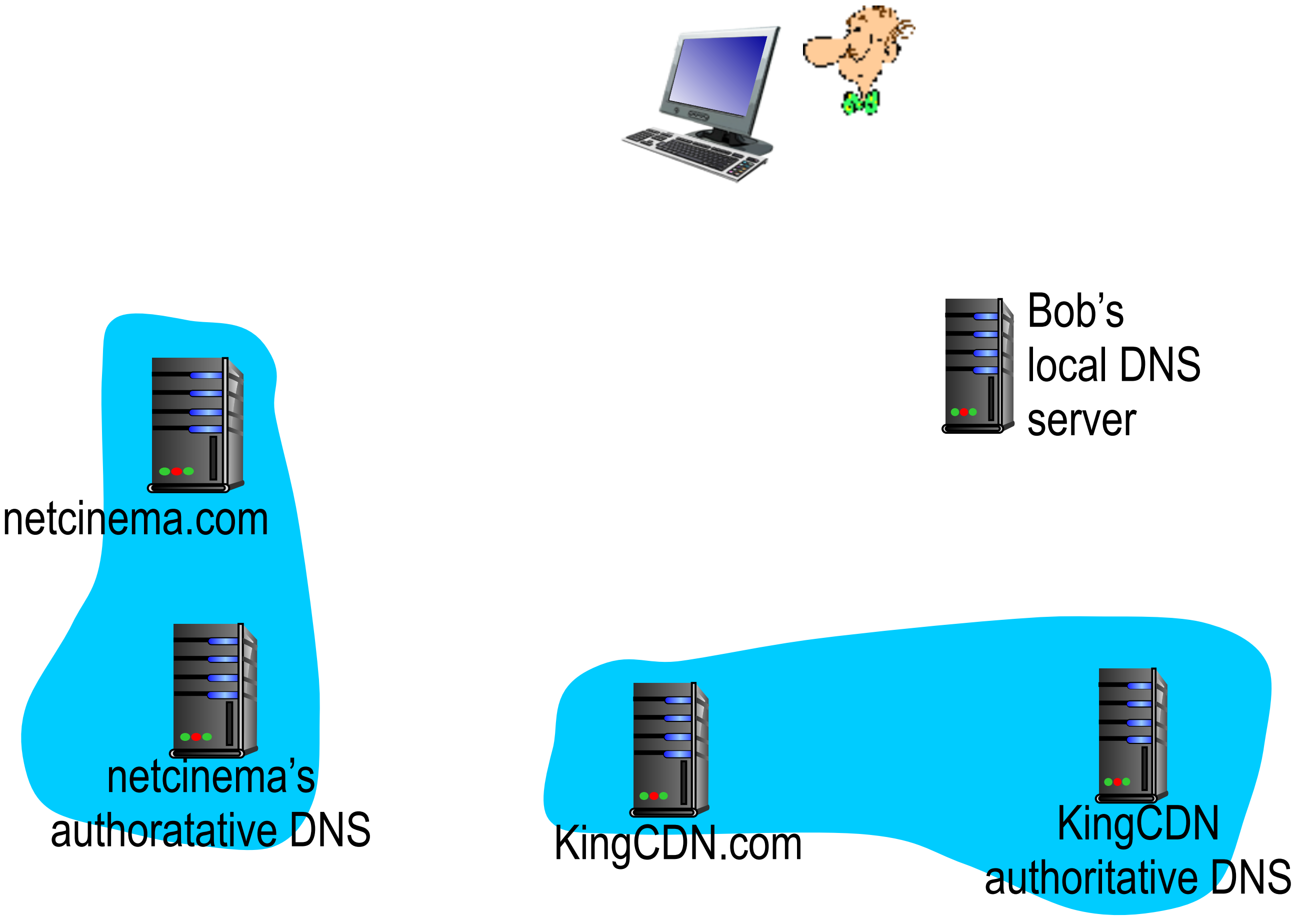
OTT challenges: coping with a congested Internet from the "edge"

- what content to place in which CDN node?
- from which CDN node to retrieve content? At which rate?

CDN content access: a closer look

Bob (client) requests video http://netcinema.com/6Y7B23V

- video stored in CDN at http://KingCDN.com/NetC6y&B23V



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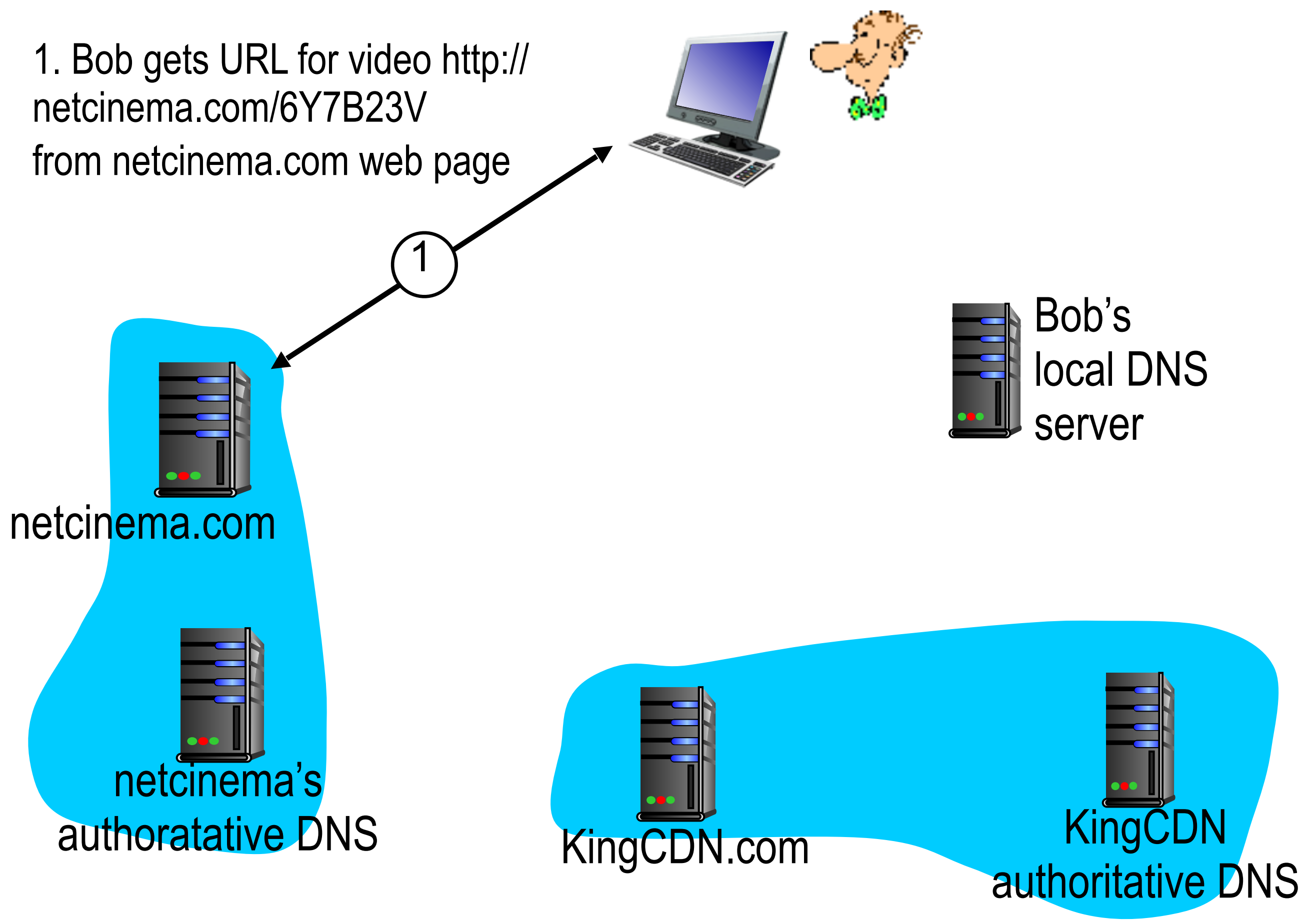

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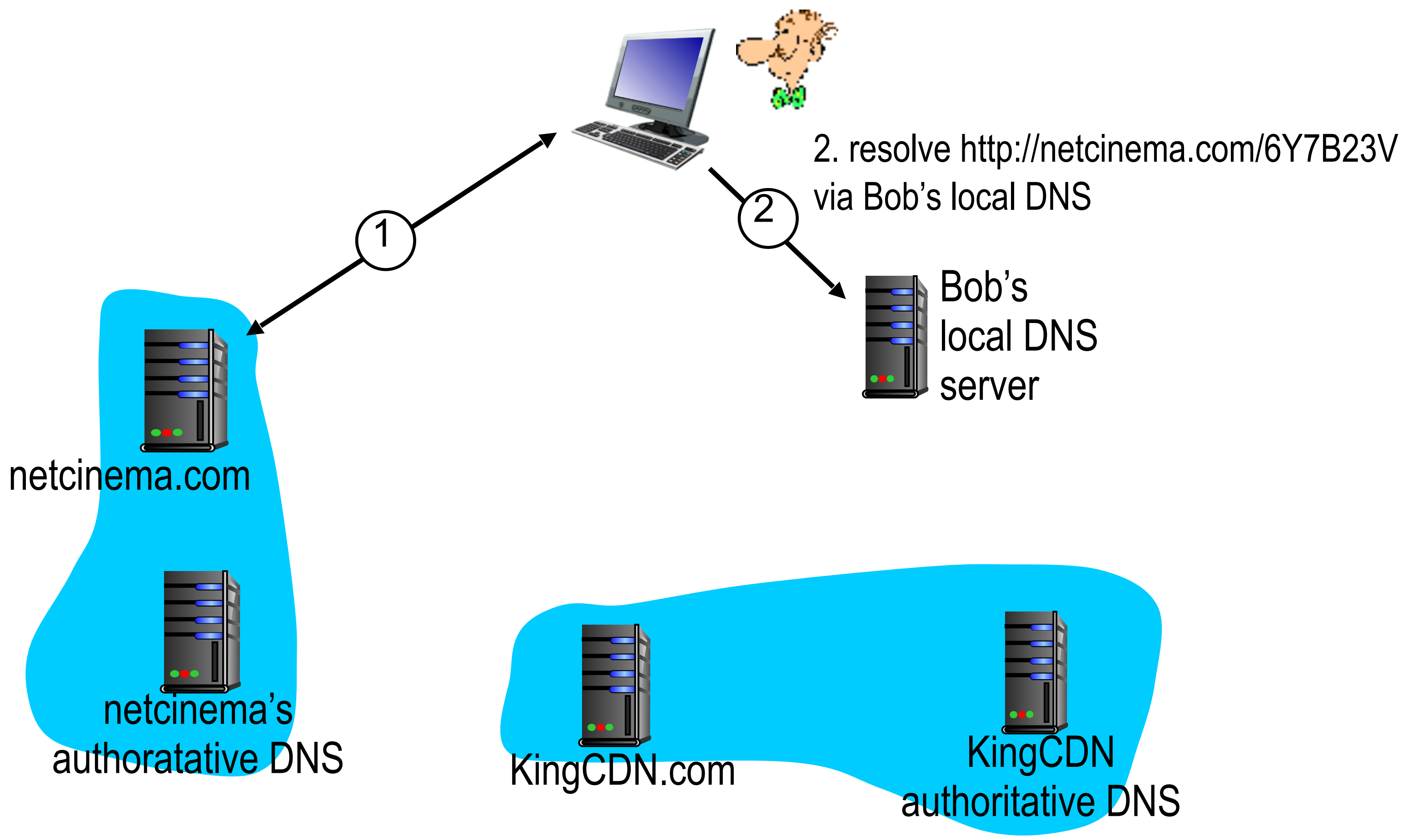

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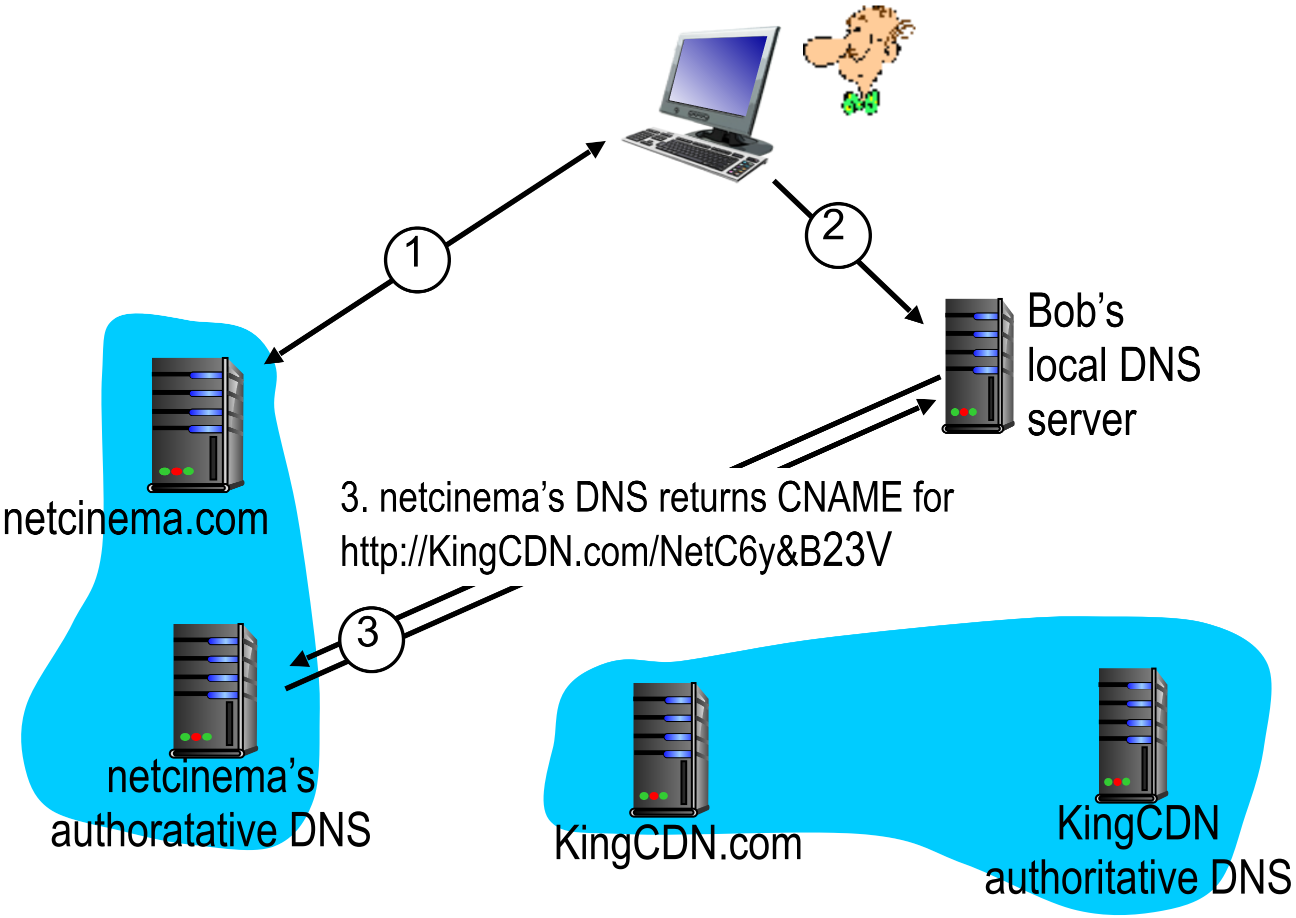

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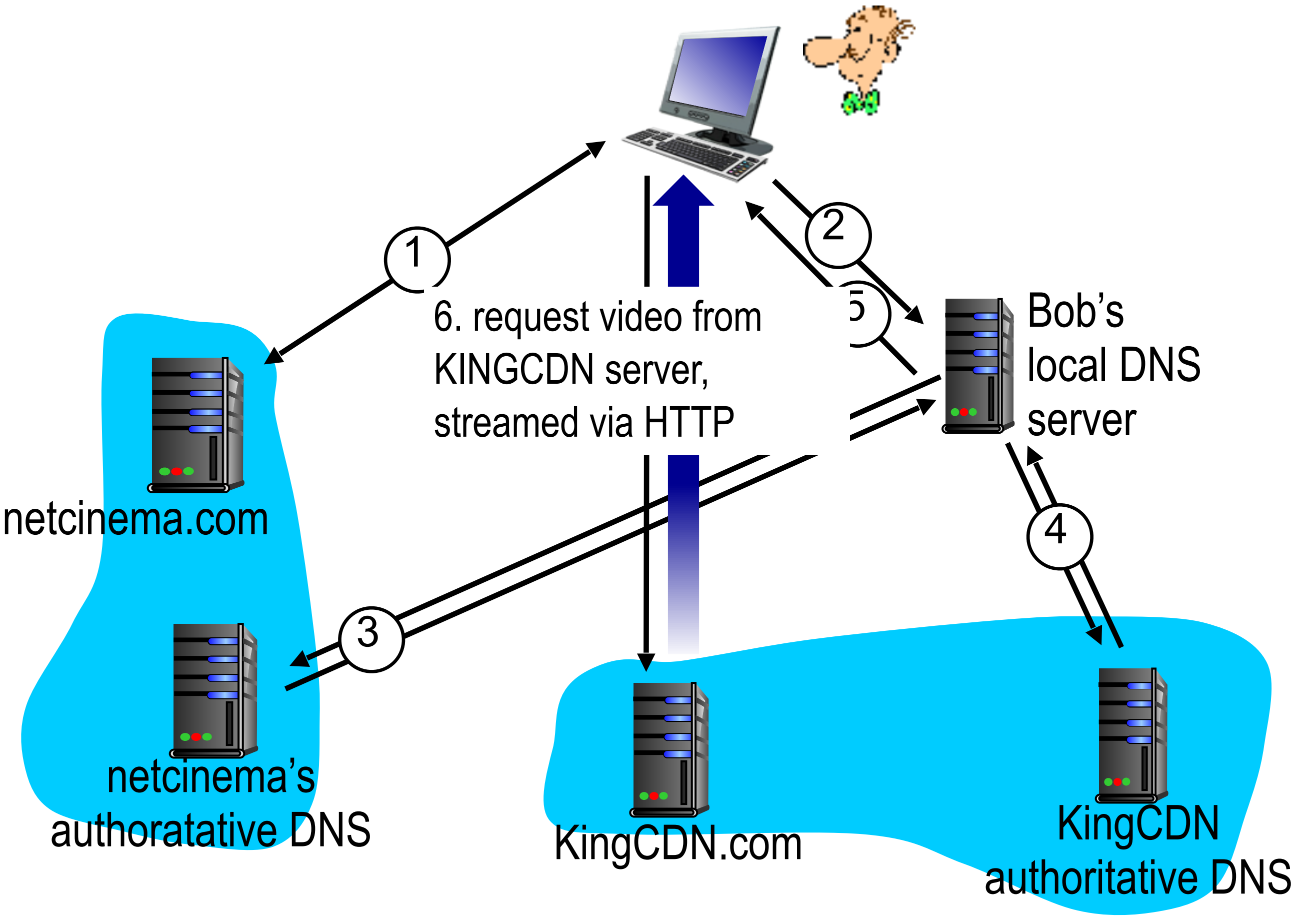

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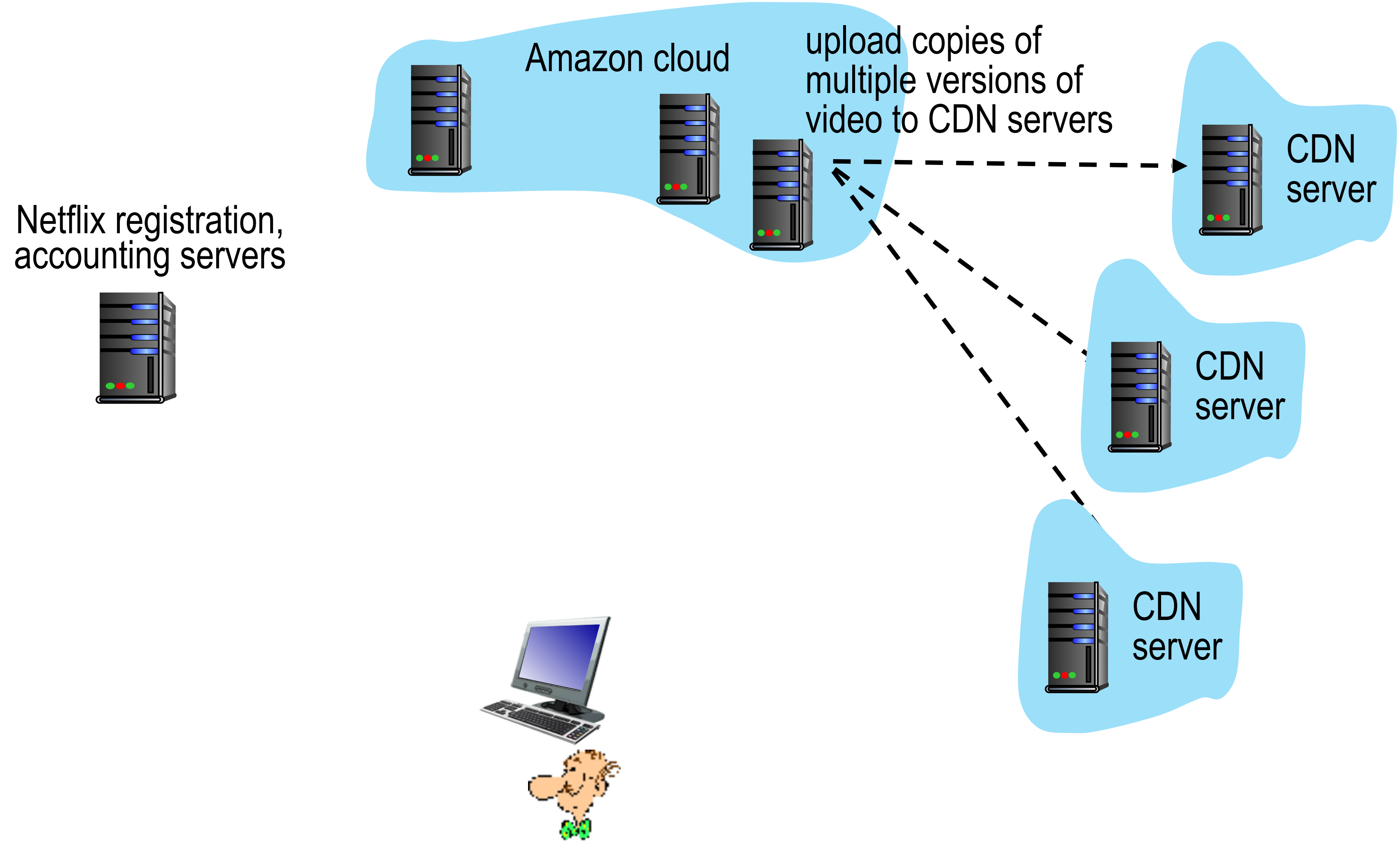

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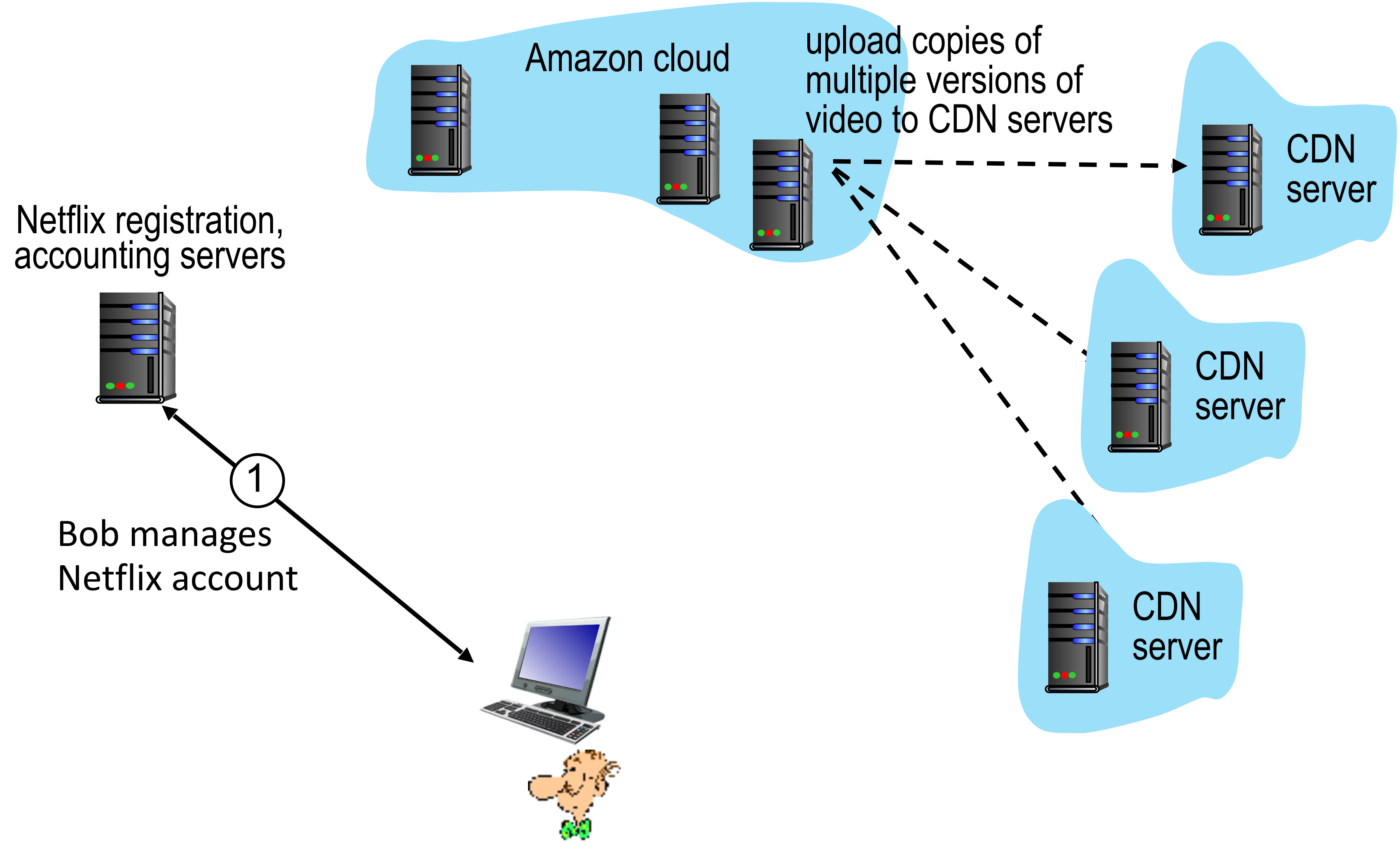

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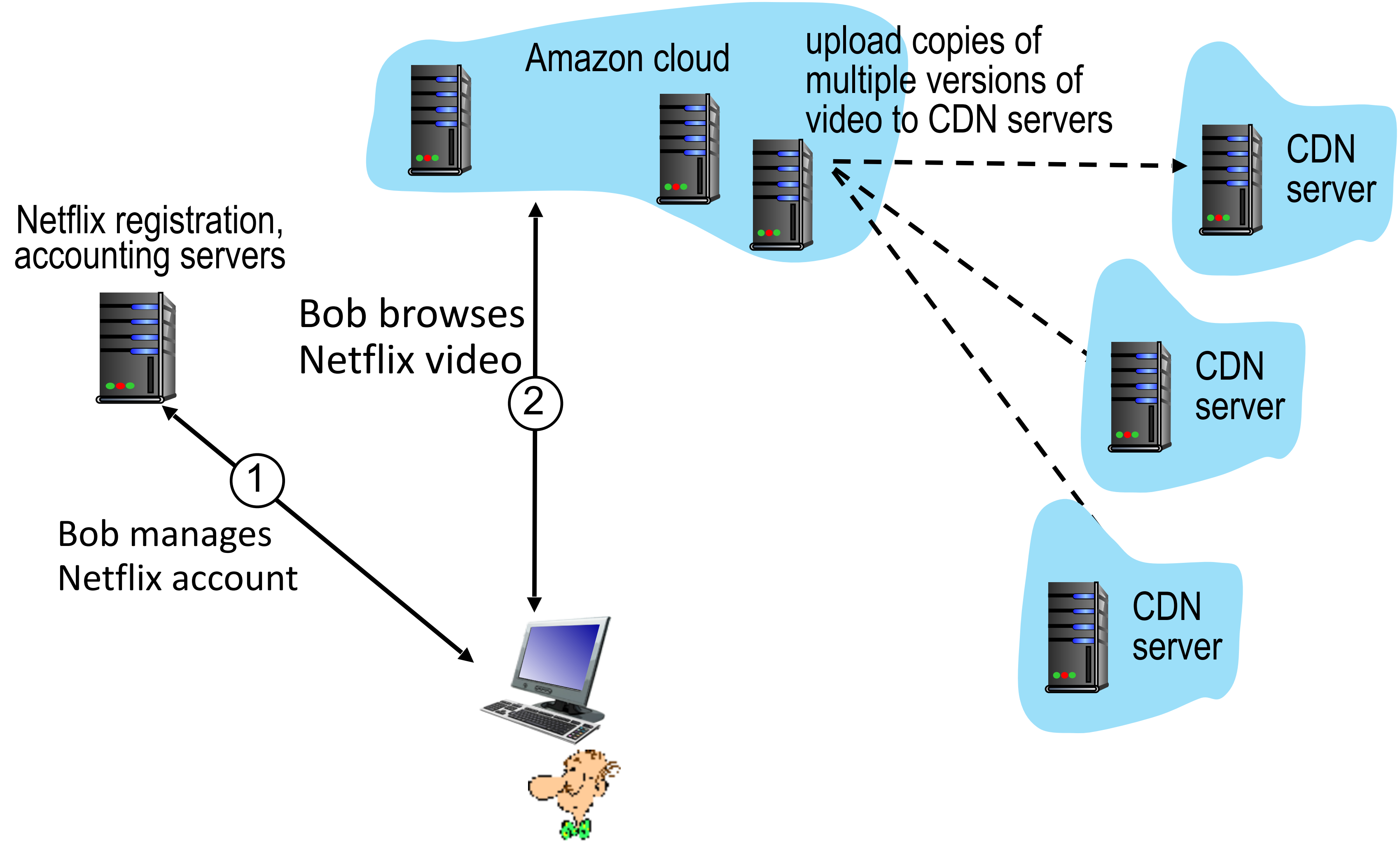

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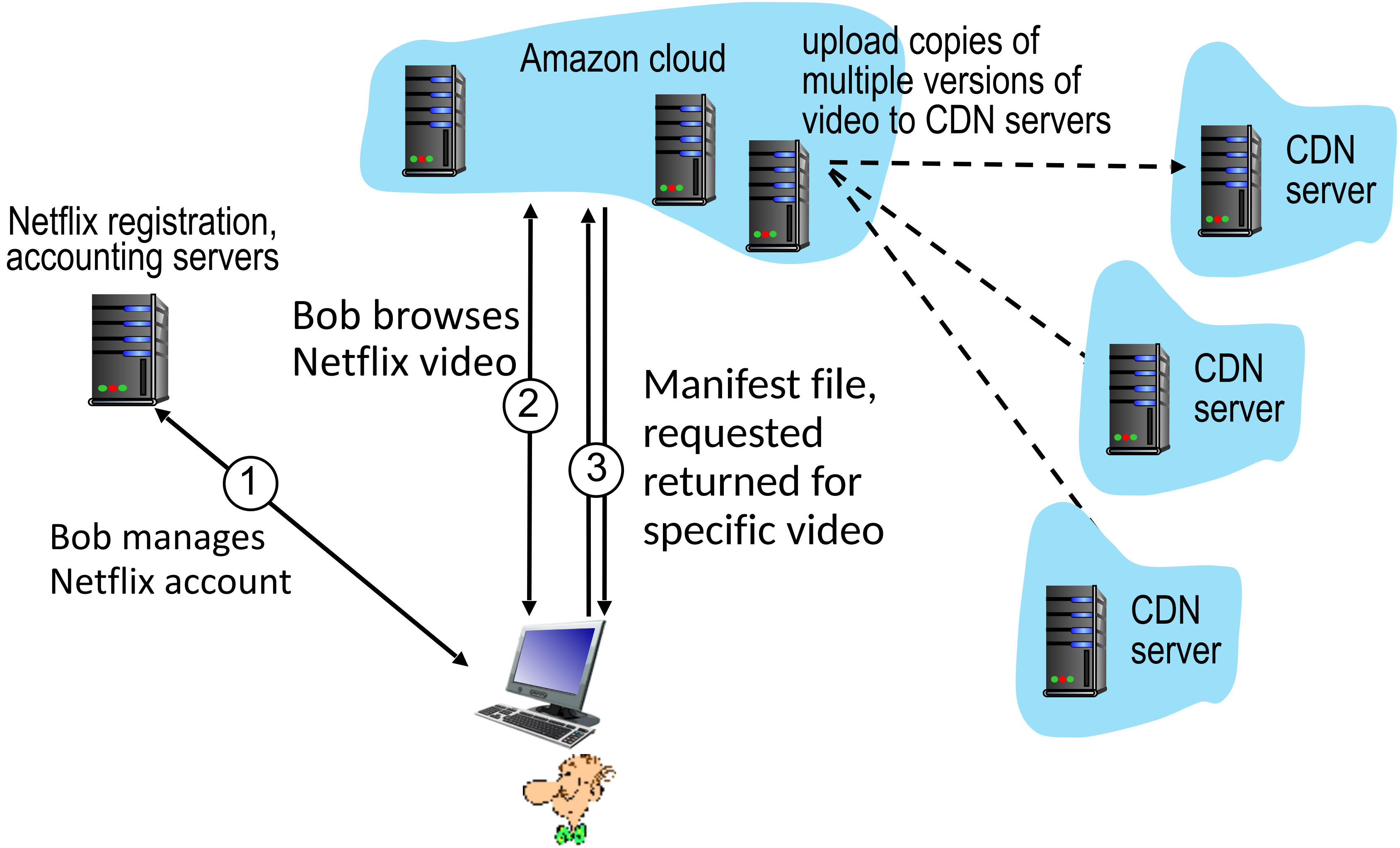

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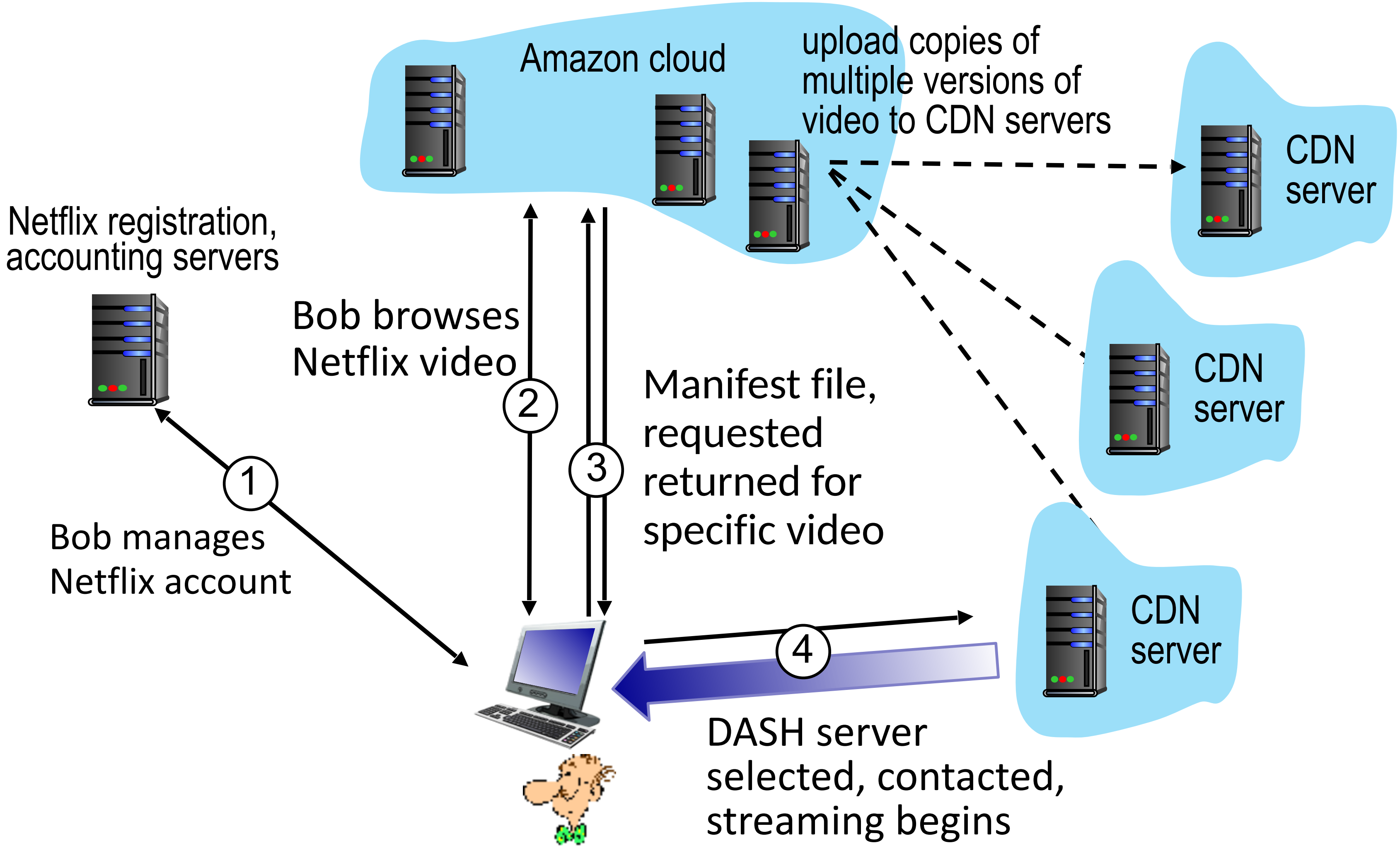

Chapter 2: Summary

our study of network application layer is now complete!

- application architectures
  - client-server
  - P2P
- application service requirements:
  - reliability, bandwidth, delay
- Internet transport service model
  - connection-oriented, reliable: TCP
  - unreliable, datagrams: UDP

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- application architectures
  - client-server
  - P2P
- application service requirements:
  - reliability, bandwidth, delay
- Internet transport service model
  - connection-oriented, reliable: TCP
  - unreliable, datagrams: UDP
- specific protocols:
  - HTTP
  - SMTP, POP, IMAP
  - DNS
  - P2P: BitTorrent
- video streaming, CDNs

Chapter 2: Summary

Most importantly: learned about *protocols*!

- typical request/reply message exchange:
  - client requests info or service
  - server responds with data, status code
- message formats:
  - *headers*: fields giving info about data
  - *data:* info(payload) being communicated

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- typical request/reply message exchange:
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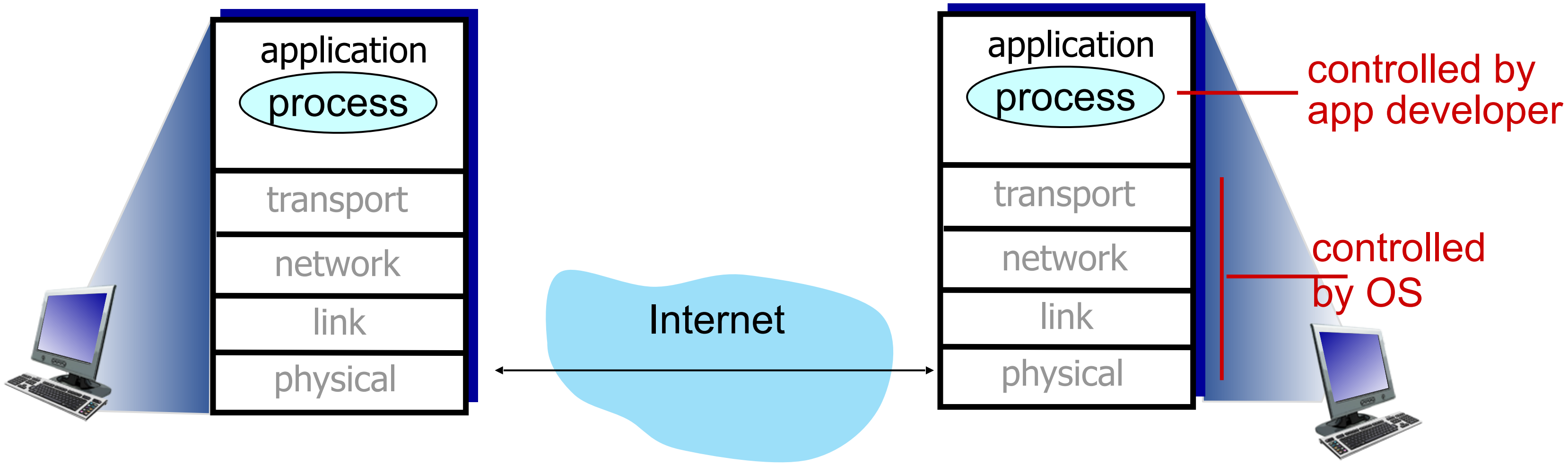
  - *data:* info(payload) being communicated

important themes:

- centralized vs. decentralized
- stateless vs. stateful
- scalability
- reliable vs. unreliable message transfer
- “complexity at network edge”

Additional Chapter 2 slides

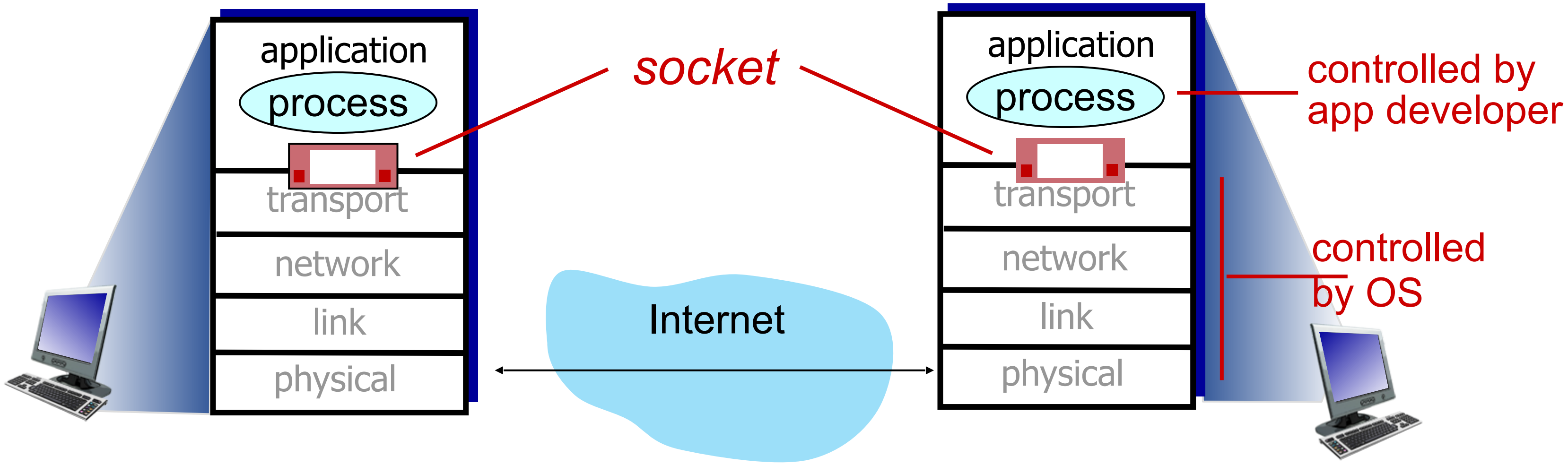
Socket programming



Socket programming

goal: learn how to build client/server applications that communicate using sockets

socket: door between application process and end-end-transport protocol



Socket programming

Two socket types for two transport services:

- *UDP:* unreliable datagram
- *TCP:* reliable, byte stream-oriented

Socket programming

Two socket types for two transport services:

- *UDP:* unreliable datagram
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Application Example:

1. client reads a line of characters (data) from its keyboard and sends data to server
2. server receives the data and converts characters to uppercase
3. server sends modified data to client
4. client receives modified data and displays line on its screen

Socket programming with UDP

UDP: no "connection" between client and server:

Socket programming with UDP

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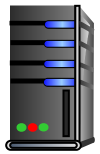

server (running on serverIP)

client

create socket, port= x:
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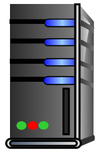

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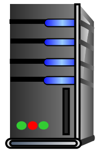

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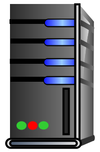

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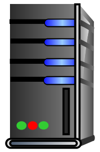

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read datagram from
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write reply to
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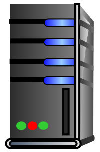

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Create datagram with serverIP address
And port=x; send datagram via
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read datagram from
clientSocket

close
clientSocket

Example app: UDP client

Python UDPClient

```
from socket import *
serverName = ‘hostname’
serverPort = 12000
clientSocket = socket(AF_INET,
                      SOCK_DGRAM)
message = raw_input(’Input lowercase sentence:’)
clientSocket.sendto(message.encode(),
                     (serverName, serverPort))
modifiedMessage, serverAddress =
                      clientSocket.recvfrom(2048)
print modifiedMessage.decode()
clientSocket.close()
```

Example app: UDP client

Python UDPClient

include Python's socket library →

```
from socket import *
serverName = 'hostname'
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Example app: UDP client

Python UDPClient

create UDP socket for server →

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```

Example app: UDP client

Python UDPClient

get user keyboard input →

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serverName = 'hostname'
serverPort = 12000
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Example app: UDP client

Python UDPClient

attach server name, port to message; send into socket →

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message = raw_input(’Input lowercase sentence:’)
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modifiedMessage, serverAddress =
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print modifiedMessage.decode()
clientSocket.close()
```

Example app: UDP client

Python UDPClient

read reply characters from socket into string →

```
from socket import *
serverName = 'hostname'
serverPort = 12000
clientSocket = socket(AF_INET,
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clientSocket.sendto(message.encode(),
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print modifiedMessage.decode()
clientSocket.close()
```

print out received string and close socket →

Example app: UDP server

Python UDPServer

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET, SOCK_DGRAM)
serverSocket.bind(('', serverPort))
print ("The server is ready to receive")
while True:
    message, clientAddress = serverSocket.recvfrom(2048)
    modifiedMessage = message.decode().upper()
    serverSocket.sendto(modifiedMessage.encode(),
                        clientAddress)
```

Example app: UDP server

Python UDPServer

create UDP socket

```
from socket import *
serverPort = 12000
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while True:
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Example app: UDP server

Python UDPServer

bind socket to local port number 12000

```
from socket import *
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from socket import *
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serverSocket = socket(AF_INET, SOCK_DGRAM)
serverSocket.bind(('', serverPort))
print ("The server is ready to receive")
while True:                                     # loop forever
    message, clientAddress = serverSocket.recvfrom(2048)
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loop forever → while True:

Example app: UDP server

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Read from UDP socket into message, getting client's address (client IP and port)

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send upper case string back to this client →

Socket programming with TCP

Client must contact server

- server process must first be running
- server must have created socket (door) that welcomes client's contact

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  - allows server to talk with multiple clients
  - *source* port numbers used to distinguish clients (more in Chap 3)

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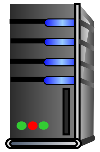
Application viewpoint

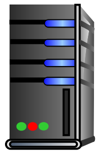
TCP provides reliable, in-order byte-stream transfer ("pipe") between client and server processes

Client/server socket interaction: TCP

 server (running on hostid)

client 

Client/server socket interaction: TCP

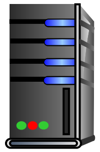


server (running on hostid)

client

create socket,
port=**x**, for incoming
request:
serverSocket = socket()

Client/server socket interaction: TCP



server (running on hostid)

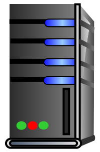
client

create socket,
port=**x**, for incoming
request:
serverSocket = socket()

↓

wait for incoming
connection request
connectionSocket =
serverSocket.accept()

Client/server socket interaction: TCP


server (running on hostid)

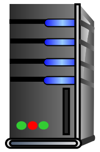
client


create socket,
port=**x**, for incoming
request:
serverSocket = socket()

wait for incoming
connection request
connectionSocket =
serverSocket.accept()

create socket,
connect to **hostid**, port=**x**
clientSocket = socket()

Client/server socket interaction: TCP



server (running on hostid)

client

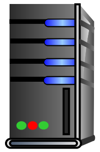
create socket,
port=**x**, for incoming
request:
serverSocket = socket()

wait for incoming
connection request
connectionSocket =
serverSocket.accept()

TCP
connection setup

create socket,
connect to **hostid**, port=**x**
clientSocket = socket()

Client/server socket interaction: TCP



server (running on hostid)

client

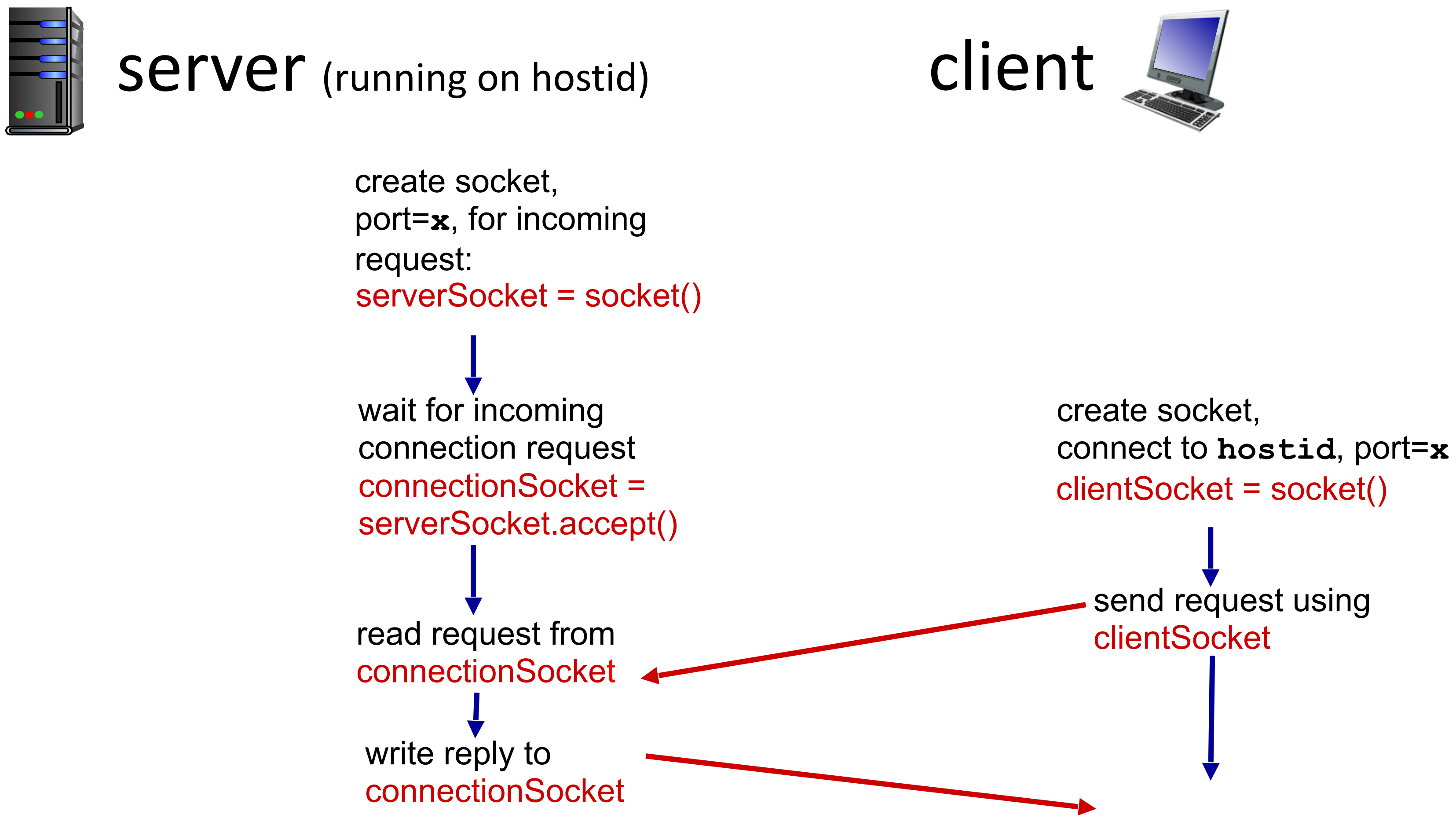
create socket,
port=**x**, for incoming
request:
serverSocket = socket()

wait for incoming
connection request
connectionSocket =
serverSocket.accept()

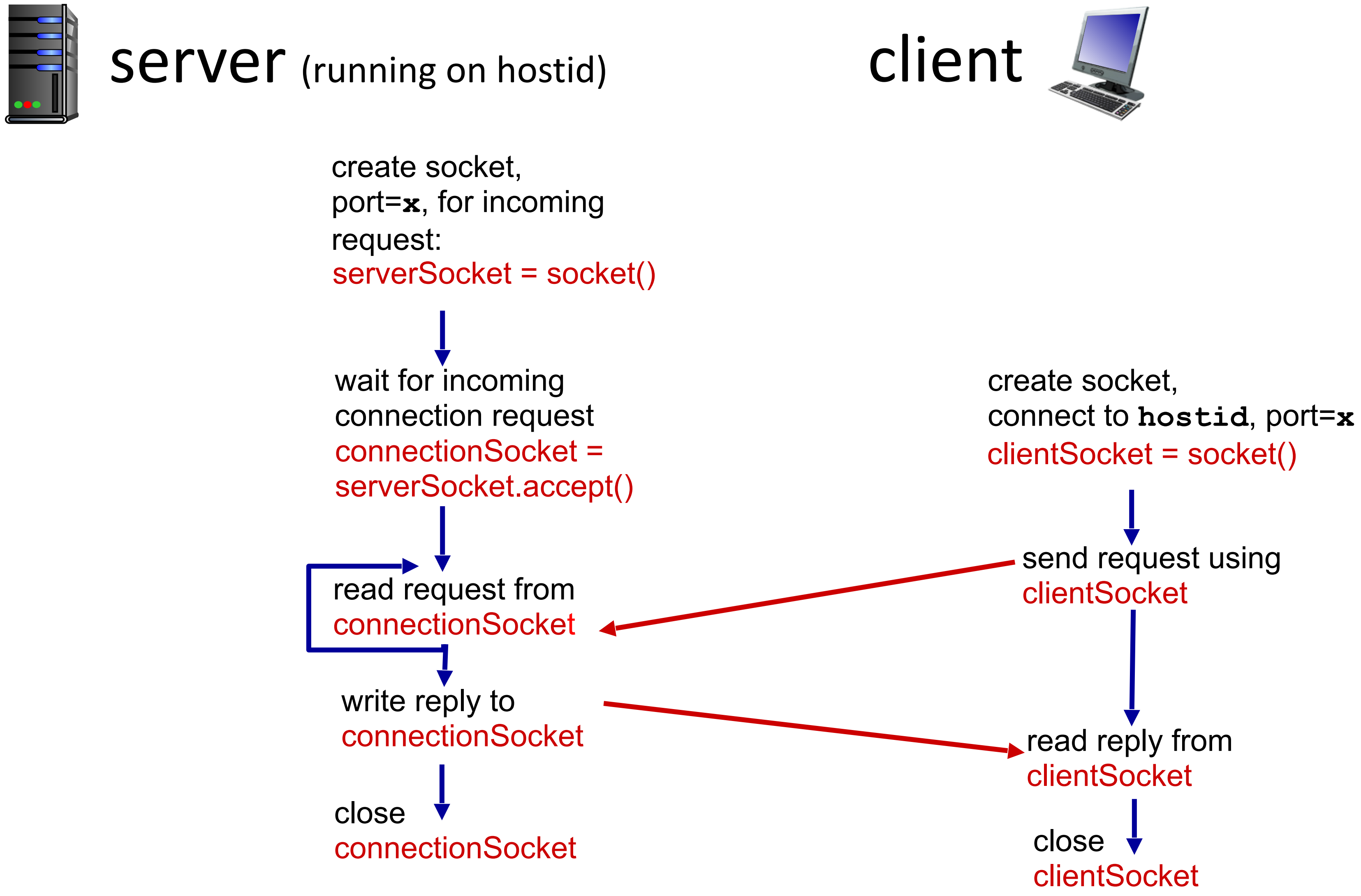
create socket,
connect to **hostid**, port=**x**
clientSocket = socket()

send request using
clientSocket

Client/server socket interaction: TCP



Client/server socket interaction: TCP



Example app: TCP client

Python TCPClient

```
from socket import *
serverName = ’servername’
serverPort = 12000
clientSocket = socket(AF_INET, SOCK_STREAM)
clientSocket.connect((serverName,serverPort))
sentence = raw_input(‘Input lowercase sentence:’)
clientSocket.send(sentence.encode())
modifiedSentence = clientSocket.recv(1024)
print (‘From Server:’, modifiedSentence.decode())
clientSocket.close()
```

Example app: TCP client

Python TCPClient

create TCP socket for server, remote port 12000

```
from socket import *
serverName = 'servername'
serverPort = 12000
clientSocket = socket(AF_INET, SOCK_STREAM)
clientSocket.connect((serverName,serverPort))
sentence = raw_input('Input lowercase sentence:')
clientSocket.send(sentence.encode())
modifiedSentence = clientSocket.recv(1024)
print ('From Server:', modifiedSentence.decode())
clientSocket.close()
```

Example app: TCP client

Python TCPClient

create TCP socket for server, remote port 12000

No need to attach server name, port

```
from socket import *
serverName = ’servername’
serverPort = 12000
clientSocket = socket(AF_INET, SOCK_STREAM)
clientSocket.connect((serverName,serverPort))
sentence = raw_input(‘Input lowercase sentence:’)
clientSocket.send(sentence.encode())
modifiedSentence = clientSocket.recv(1024)
print (‘From Server:’, modifiedSentence.decode())
clientSocket.close()
```

Example app: TCP server

Python TCPServer

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind((‘’,serverPort))
serverSocket.listen(1)
print ‘The server is ready to receive’
while True:
    connectionSocket, addr = serverSocket.accept()

    sentence = connectionSocket.recv(1024).decode()
    capitalizedSentence = sentence.upper()
    connectionSocket.send(capitalizedSentence.
                                        encode())
    connectionSocket.close()
```

Example app: TCP server

Python TCPServer

create TCP welcoming socket

```
 from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind((‘’,serverPort))
serverSocket.listen(1)
print ‘The server is ready to receive’
while True:
     connectionSocket, addr = serverSocket.accept()

     sentence = connectionSocket.recv(1024).decode()
     capitalizedSentence = sentence.upper()
     connectionSocket.send(capitalizedSentence.
                                                      encode())
     connectionSocket.close()
```

Example app: TCP server

Python TCPServer

server begins listening for incoming TCP requests

```
 from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind((‘’,serverPort))
serverSocket.listen(1)
print ‘The server is ready to receive’
while True:
     connectionSocket, addr = serverSocket.accept()

     sentence = connectionSocket.recv(1024).decode()
     capitalizedSentence = sentence.upper()
     connectionSocket.send(capitalizedSentence.
                                                 encode())
     connectionSocket.close()
```

Example app: TCP server

Python TCPServer

loop forever

```
 from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind((‘’,serverPort))
serverSocket.listen(1)
print ‘The server is ready to receive’
while True:
     connectionSocket, addr = serverSocket.accept()

     sentence = connectionSocket.recv(1024).decode()
     capitalizedSentence = sentence.upper()
     connectionSocket.send(capitalizedSentence.
                                              encode())
     connectionSocket.close()
```

Example app: TCP server

Python TCPServer

```
 from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind((‘’,serverPort))
serverSocket.listen(1)
print ‘The server is ready to receive’
while True:
     connectionSocket, addr = serverSocket.accept()

     sentence = connectionSocket.recv(1024).decode()
     capitalizedSentence = sentence.upper()
     connectionSocket.send(capitalizedSentence.
                                              encode())
     connectionSocket.close()
```

server waits on accept() for incoming requests, new socket created on return

Example app: TCP server

Python TCPServer

```
 from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind((‘’,serverPort))
serverSocket.listen(1)
print ‘The server is ready to receive’
while True:
     connectionSocket, addr = serverSocket.accept()

     sentence = connectionSocket.recv(1024).decode()
     capitalizedSentence = sentence.upper()
     connectionSocket.send(capitalizedSentence.
                                        encode())
     connectionSocket.close()
```

read bytes from socket (but not address as in UDP)

Example app: TCP server

Python TCPServer

```
from socket import *
serverPort = 12000
serverSocket = socket(AF_INET,SOCK_STREAM)
serverSocket.bind((‘’,serverPort))
serverSocket.listen(1)
print ‘The server is ready to receive’
while True:
    connectionSocket, addr = serverSocket.accept()

    sentence = connectionSocket.recv(1024).decode()
    capitalizedSentence = sentence.upper()
    connectionSocket.send(capitalizedSentence.
                                              encode())
    connectionSocket.close()
```

close connection to this client (but *not* welcoming socket)